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TAMPERE UNIVERSITY OF TECHNOLOGY

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WATER CONTENT DETERMINATION OF SOFT FINNISH CLAYS USING ELECTRICAL CONDUCTIVITY MEASUREMENTS

Master of Science Thesis

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ABSTRACT

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This thesis is made in accordance to evaluate a possibility to use electrical conductivity measurements for determination of geotechnical parameters. The main goal of this thesis is to find a way to determine water content of soft Finnish clays using electrical conductivity measurements.

This thesis is divided into two parts that are literature study and experimental part. In literature study properties of clay and its formation, as well as modelling and measuring electrical conductivity of soils are examined.

In experimental part, electrical conductivity measurements, done for Finnish soft clay deposits, are compared with laboratory data to find affecting relations between those. Totally of seven sites were investigated. Electrical conductivity measurements were done with conductivity module attached on top of a CPTU cone.

Based on experimental results, pore water conductivity (salinity) controls the conductivity of tested clays, and a strong, linear correlation between soil and pore water conductivities is found. Water or clay content did not show any effect on results. However, while water content data is divided based on soil conductivity, some kind of correlation between water content and soil conductivity could be found for high conductivity (> 225 mS/m) clays. To confirm existence of this relation, more measurements using high conductivity clays should be done.

Of other geotechnical parameters, plasticity and liquidity indexes as well as sensitivity and remolded shear strength seem to correlate with soil conductivity. Liquidity index and sensitivity decreases with increasing soil conductivity and an upper limit as a function of conductivity can be sketched. On the other hand, plasticity index and remolded shear strength seem to increase with increasing soil conductivity, but the correlations are not very strong.

Main goal of the theses was not achieved, since water content, at least in general level, does not seem to correlate with electrical conductivity of soil. However, as strong correlation between soil and pore water conductivities was found, it would be interesting to study possibility to use conductivity measurements for evaluation of corrosion environment. In addition, use of conductivity measurements for soil contamination investigations could be studied.

TIIVISTELMÄ

MARKUS HAIKOLA: Suomalaisten savien vesipitoisuuden määrittäminen sähkönjohtavuusmittauksella.
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Tämä diplomityö tehtiin maan sähkönjohtavuusmittausten mahdollisuuksien arvioimiseksi. Lähtökohtana oli selvittää, onko sähkönjohtavuuden perusteella mahdollista määrittää maan geoteknisiä parametreja. Työn päätavoitteena oli löytää menetelmä suomalaisten pehmeiden savien vesipitoisuuden määrittämiseksi sähkönjohtavuuden perusteella.

Tämä diplomityö on jaettu kahteen osaan, jotka ovat kirjallisuusselvitys ja kokeellinen osuus. Kirjallisuusselvityksessä tutkitaan saven ominaisuuksia ja muodostumista sekä maan sähkönjohtavuuden mallintamista ja mittaamista.

Kokeellisessa osuudessa pehmeille suomalisille saville mitattuja sähkönjohtavuuksia verrataan laboratorioissa mitattuihin geoteknisiin ominaisuuksiin ja selvitetään näiden välisiä yhteyksiä. Tutkittuja kohteita oli yhteensä seitsemän. Sähkönjohtavuusmittaukset suoritettiin CPTU-kärjen yläpuolelle kiinnitettävällä sähkönjohtavuusmoduulilla.

Kokeellisen osuuden tulosten perusteella huokosveden sähkönjohtavuus (suolapitoisuus) määrittää tutkittujen savien sähkönjohtavuuden. Näiden välillä havaittiin vahva lineaarinen korrelaatio. Vesi- tai savipitoisuudella ei havaittu olevan vaikutusta mitattuun sähkönjohtavuuteen. Kuitenkin kun vesipitoisuustulokset lajiteltiin sähkönjohtavuuksien perusteella eri suuruusluokkiin, pystyttiin korkean sähkönjohtavuuden (> 225 mS/m) saville määrittämään lineaarinen yhteys vesipitoisuuden ja sähkönjohtavuuden välille. Tällaisen yhteyden olemassa olon varmistamiseksi olisi kuitenkin tehtävä lisämittauksia korkean sähkönjohtavuuden savilla.

Muiden geoteknisten parametrien kohdalla selvimmät yhteydet sähkönjohtavuuteen löytyivät plastisuus- ja juoksevuusindeksistä sekä häiritystä leikkauslujuudesta ja sensitiivisyydestä. Juoksevuusindeksi ja sensitiivisyys pienenevät maan sähkönjohtavuuden kasvaessa ja näille on mahdollista määritellä ylärajakäyrä sähkönjohtavuuden funktiona. Plastisuusindeksi ja häiritty leikkauslujuus taas näyttävät kasvavan sähkönjohtavuuden kasvaessa, mutta tämä korrelaatio on varsin heikko.

Diplomityön päätavoitetta ei saavutettu, sillä vesipitoisuus ei ainakaan yleisesti näytä korreloivan sähkönjohtavuuden kanssa. Toisaalta koska huokosveden sähkönjohtavuus näyttää korreloivan selkeästi maan sähkönjohtavuuden kanssa, jatkotutkimuksissa olisi mielenkiintoista selvittää sähkönjohtavuusmittausten soveltuvuutta korroosio-olosuhteiden ja maan pilaantuneisuuden arviointiin.

PREFACE

This thesis is made as a part of Tampere University of Technology's Fincone project funded by Finnish Transport Agency.

I would like to thank Professor Tim Länsivaara for offering possibility to conduct this thesis and Finnish Transport Agency for funding it. Many thanks for Professor Länsivaara also for guidance and examination. Thanks goes also for coworkers at Earth and Foundation Structures research group for providing inspiring working environment. Special thanks to researcher Juha Selänpää, with whom I have had pleasure to work with. Interesting conversations with Juha have increased my interest to geotechnical engineering. Many thanks also to my wife Kati and my parents for providing irreplaceable support during this work.

In Tampere, Finland, on 21 August 2018

Markus Haikola

CONTENTS

1. INTRODUCTION 1
2. CLAY MATERIAL 4
2.1 Clay and nonclay minerals 4
2.2 Clay-electrolyte system 11
2.3 Clay fabric 13
3. CLAY FORMATION 15
3.1 Geologic cycle 15
3.2 Sedimentation process 16
3.3 Effect of the sedimentation environment 18
3.4 After sedimentation processes 18
4. SEDIMENTATION ENVIRONMENT AND GEOTECHNICAL PROPERTIES OF FINNISH CLAYS 20
4.1 Weichselian glacier in Finland 20
4.2 Phases of the Baltic Sea basin after Weichselian 21
4.3 Properties of fine-grained sediments in Finland 22
5. ELECTRICAL CONDUCTIVITY OF SOILS 26
5.1 Electrical conductivity in general 26
5.2 Soil conductivity models 26
5.3 Soil conductivity measurements 31
5.4 Environmental and measurement properties affecting on conductivity 35
5.5 Soil properties affecting on electrical conductivity 38
6. TESTING PROCEDURE AND SITES 43
6.1 Field tests 43
6.2 Laboratory tests 46
6.3 Testing sites 52
6.3.1 Perniö 53
6.3.2 Sipoo 55
6.3.3 Paimio 57
6.3.4 Kotka 238 59
6.3.5 Kotka 233 61
6.3.6 Masku 63
6.3.7 Murro 65
6.4 Conclusion of the sites 66
6.5 Assumed errors in field and laboratory tests 66
7. CORRELATIONS BETWEEN ELECTRICAL CONDUCTIVITY AND GEOTECHNICAL PARAMETERS 68
7.1 Correlations to parameters describing soil composition 69
7.2 Correlations to plastic properties 74
7.3 Correlation to strength properties 77
7.4 Discussion of the results and comparison to other studies 80

8. CONCLUSIONS 84
REFERENCES 87

APPENDIX A: PERNIÖ SITE INVESTIOGATION RESULTS

APPENDIX B: SIPOO SITE INVESTIOGATION RESULTS

APPENDIX C: PAIMIO SITE INVESTIOGATION RESULTS

APPENDIX D: KOTKA 238 SITE INVESTIOGATION RESULTS

APPENDIX E: KOTKA 233 SITE INVESTIOGATION RESULTS

APPENDIX F: MASKU SITE INVESTIOGATION RESULTS

APPENDIX G: MURRO SITE INVESTIOGATION RESULTS

LIST OF FIGURES

Figure 1. *Structure of silica tetrahedron sheet (Mitchell 1976, p. 29). 4*
Figure 2. *Structure of octahedron sheet (Mitchell 1976, p. 30). 5*
Figure 3. *Illustration of kaolinite structure and its unit cell (Mitchell 1976, p. 34)..... 7*
Figure 4. *Illustration of smectite group (montmorillonite) mineral structure and its unit cell (Mitchell 1976, p. 37). 8*
Figure 5. *Structure of muscovite mica unit cell (Mitchell 1976, p. 40). 9*
Figure 6. *Structures of a) illite and b) vermiculite (Mitchell 1976, p. 40). 10*
Figure 7. *Structure of chlorite (Mitchell 1976, p. 42) 10*
Figure 8. *Ion concentration distribution in diffusion double layer around clay particle. (van Olphen 1977, p. 32) 12*
Figure 9. *Electric potential distribution of the DDL with two different pore water electrolytic concentrations or two different valence cations (adapted from Helle 2017, p. 12). 12*
Figure 10. *Flocculation modes of clay particles (van Olphen 1977). 14*
Figure 11. *Geologic cycle of rock and soil (Mitchell 1976, p. 48). 15*
Figure 12. *Erosion and transportation velocities of air and water flows for different particle sizes (Mitchell 1976, p. 62). 17*
Figure 13. *Phases of the Baltic Sea basin (Gardemeister 1975, p. 11). 21*
Figure 14. *Distribution of clays in southern and central parts of Finland (Salonen et al. 2002, p. 55) 23*
Figure 15. *Correlation between electrical conductivity normalized with pore water conductivity and porosity (Friedman & Robinson 2002, p. 7). 28*
Figure 16. *Schematic and simplified illustrations of the three phase model (Rhoades et al. 1989, p. 434). 30*
Figure 17. *Potential of a point-form current electrode in a homogeneous half space (Peltoniemi 1988, p. 131). 32*
Figure 18. *Basis of general four electrode method (Peltoniemi 1988, p. 144). 33*
Figure 19. *Electrode arrays used in ERT measurements (Mohamed & Paleologos 2017, p. 504) 34*
Figure 20. *Typical electrical conductivity response of clayey soil against the increasing AC measurement frequency (Rinaldi & Cuestas 2002, p. 826)..... 36*
Figure 21. *Frequency dependency of electrical conductivity of NaCl electrolyte (pore water) in different concentrations (Rinaldi & Cuestas 2002, p. 827)..... 37*
Figure 22. *Frequency dependency of electrical conductivity of constructed soil samples with different pore water salinities (Rinaldi & Cuestas 2002, p. 828) 37*
Figure 23. *Effect of pore water ionic composition on electrical conductivity of soil (Rinaldi & Cuestas 2002, p. 829). 38*

Figure 24. *Electrical conductivity against pore water conductivity of sand samples containing different amounts of clay (Wildenschild et al. 2000, p. 3086).* *39*
Figure 25. *Resitivity of undisturbed and disturbed natural clay samples in different stress states (Fukue et al. 1999).* *40*
Figure 26. *Clay content dependency of porosity for sand-clay mixtures (Shevnin et al. 2007, p. 266)* *41*
Figure 27. *Theoretical model and measurement results of relation between apparent resistivity and clay content (Shevnin et al. 2007).* *41*
Figure 28. *TUTs drill rig (Di Buo 2015)* *44*
Figure 29. *Conductivity module (Selänpää 2014).* *44*
Figure 30. *Electrode arrangement and measurements of the Icone conductivity module (Icone Conductivity Module, easy acces to additional data with a click-on module 2015)* *45*
Figure 31. *Crystal water correction in organic content determination (Suomen geoteknillinen yhdistys 1985)* *48*
Figure 32. *Pore water extruder (left) and conductivity probe (right).* *49*
Figure 33. *Topography and topsoil formations of Perniö site (Taustakartta ; Rinnevarjostus ; Maaperä)* *53*
Figure 34. *Topography and topsoil formations of the Sipoo site (Taustakartta ; Rinnevarjostus ; Maaperä).* *55*
Figure 35. *Topography and topsoil formations of the Paimio site (Taustakartta ; Rinnevarjostus ; Maaperä).* *57*
Figure 36. *Topography and topsoil formations of the Kotka 238 site (Taustakartta ; Rinnevarjostus ; Maaperä)* *59*
Figure 37. *Topography and topsoil formations of the Kotka 233 site (Taustakartta ; Rinnevarjostus ; Maaperä)* *61*
Figure 38. *Topography and topsoil formations of the Masku site (Maaperä ; Rinnevarjostus ; Taustakartta)* *63*
Figure 39. *Topography and topsoil formations of the Murro site (Taustakartta ; Rinnevarjostus ; Maaperä).* *65*
Figure 40. *Correlation between soil conductivity and water content.* *69*
Figure 41. *Correlation between soil conductivity and water content grouped based on sedimentation environment.* *70*
Figure 42. *Correlation between soil conductivity and clay content.* *71*
Figure 43. *Correlation between soil and pore water conductivity.* *72*
Figure 44. *Correlation between soil conductivity and pore water salinity.* *73*
Figure 45. *Correlation between soil conductivity and plasticity index* *74*
Figure 46. *Correlation between soil conductivity and liquidity index.* *75*
Figure 47. *Correlation between soil conductivity and activity.* *76*
Figure 48. *Correlation between soil conductivity and intact undrained shear strength.* *77*

Figure 49. *Correlation between soil conductivity and remolded undrained shear strength.* *78*
Figure 50. *Correlation between soil conductivity and sensitivity.* *79*
Figure 51. *Comparison of resistivity versus salinity plots a) this thesis, b) (Long et al. 2012, p. 1162), and c) (Montafia 2013, p. 48).* *81*
Figure 52. *Comparison of resistivity versus water content plots a) this theisis, b) Long et al. (2012, p. 1165), and c) Montafia (2013, p. 49).* *82*

LIST OF SYMBOLS AND ABBREVIATIONS

AC	alternating current
CPTU	cone penetration test with pore pressure measurement
DC	direct current
DDL	diffusion double layer
DSS	direct simple shear
e.m.f	electro motive force
ERT	electrical resistivity tomogrpahy
FTA	Finnish Transport Agency
FVT	field vane test
TUT	Tampere University of technology
SWT	Swedish Weight Sounding

a	constant in Rhoades et al. (1976) two phase model, electrode distance
b	constant in Rhoades et al. (1976) two phase model
E	electric field
F	formation factor
F^*	formation factor
f	volumetric fraction
f_T	temperature correction factor
I	electric current
J	current density
K	geometrical coefficient
LI	liquidity index
LL	liquid limit
m	cementation index
n	porosity, volumetric fraction
PI	plasticity index
PL	plastic limit
r	distance from electrode
r_{xy}	distance between electrodes X and Y
s_u	intact undrained shear strength
s_{ur}	remolded undrained shear strength
T	transmission coefficient
V	potential of electrode
ΔV	potential difference
w	water content

θ	volumetric water content
θ_{sc}	volumetric water content of continuous path of solid matrix
θ_{ss}	volumetric water content of solid matrix coupled in series with pore water
θ_w	total volumetric water content
θ_{wc}	volumetric water content of free pore water
θ_{ws}	volumetric water content of free pore water coupled in series with solid matrix
$1/\kappa$	thickness of diffusion double layer
ρ	resistivity
σ	electrical conductivity (of soil)

σ_{25}	electrical conductivity in 25 °C
σ_a	apparent electrical conductivity of soil
σ'_p	preconsolidation pressure
σ_s	electrical conductivity of solid matrix or particle surface
σ_T	electrical conductivity in temperature T
σ_w	electrical conductivity of pore water or surrounding matrix
σ_{wc}	electrical conductivity of free pore water
σ_{ws}	electrical conductivity of pore water coupled in series with solid matrix
σ_w	electrical conductivity of pore water, electrical conductivity of

1. INTRODUCTION

Due to urbanization, more people are moving into cities rising needs for increasing construction works. Since on previous times construction works has been concentrated to areas of good subsoils, there is about to be lack of those and plots with worse and worse subsoils needs to be constructed on. Because of that, meaning of ground investigations becomes greater. On the other hand, costs of ground investigations needs to be controlled giving desire to develop new methods.

This Master of Science thesis is made as a part of Tampere University of Technology's (TUT) Fincone project funded by Finnish Transport Agency (FTA). Goal of the Fincone project is to study, develop, and promote use of cone penetration test (CPTU) in Finland. Advance of using CPTU is that soil layers and geotechnical parameters of those may be defined in more detailed manner comparing to traditional methods.

During CPTU sounding, complementary properties of soils can be measured, and electrical conductivity is one of those. Electrical conductivity measurement does not slow down regular CPTU sounding, and cost of conductivity module is not very high. These factors make studying possibilities of electrical conductivity measurements interesting.

Electrical conductivity measurements have been used for generalized site characterization and locating contaminated soils. Also applications for searching oil and ore have been used. Agricultural applications play important role in the field of electrical conductivity measurements. There the importance is in determination of nutrient amounts and water content. Particularly with CPTU sounding electrical conductivity or resistivity measurements have been used to improve locating sensitive or quick clay layers. However, these measurements have not been used for determination of geotechnical parameters to be used for design.

Goal of this thesis is to see, how electrical conductivity of soft Finnish clays correlate with geotechnical parameters. Main interest is in water content, which could be used for preliminary settlement calculations. Inspiration for finding this kind of relation came from report (Törnqvist et al. 2001) where continuous settlement profile of road was tried to calculate based on water contents determined by resistivity measurements. There the idea was to use site specific correlation between water content and resistivity. The water content data was expanded through the whole layer using resistivity measurements.

In form of a research question, the goal of this thesis can be expressed as: *How water content and other geotechnical parameters of soft Finnish clays correlates with its electrical conductivity?* To be able to answer this question, following sub questions are posed:

1. What are properties of clay related to conductivity?
2. How are clays formed and how this effects on its conductivity?
3. How is soil conductivity measured?
4. What are the main factors affecting on soil electrical conductivity?

Answer to question 1 is found through literature study and specifically for Finnish clays with experimental results. Answers for questions 2–4 are found by literature study where soil formation as well as measuring and modelling of soil electrical conductivity is examined. Knowledge, gained of the literature study, is used to complete ground investigations made in framework of the Fincone project. Based on ground investigations, correlations between water content and other geotechnical parameters and electrical conductivity are tried to find.

The interest is not in the water content itself, but in other properties that can be estimated based on it. Main thing is to evaluate deformation properties of soil for preliminary settlement calculations, and to expand properties to wider range in the investigated deposit as was done in report (Törnqvist et al. 2001). Correlations to other geotechnical properties are tried to find in accordance to expand usability of the electrical conductivity measurements. This can be done, since extensive ground investigations are made during Fincone project, and lot of index, strength and deformation properties are defined from the different sites.

This thesis is divided into two main parts that are literature study and experimental part. Chapters 2–4 belong to the literature study part and 5–6 to the experimental study part. Chapter 2 defines building blocks of clays. Defining starts from clay minerals and goes till pore water and interaction of those two. Finally clay structure and non-clay minerals found in clays are defined.

Formation of clay is presented in chapter 3. First, general about soil formation is discussed, and after that processes specific for clay formation are defined. At last, sedimentation environments of Finnish clays are presented including different phases of the Baltic Sea.

On chapter 4, modelling and measuring of soil electrical conductivity is presented. Also factors effecting on soil conductivity are examined.

Experimental methods are defined in chapter 5. Presentation of the sites and results includes to that also. Correlations between soil electrical conductivity and geotechnical parameters are presented in chapter 6.

Chapter 7 composes of discussion of the experimental results and comparison of those to other studies of this topic. Finally, chapter 8 concludes this thesis.

2. CLAY MATERIAL

Term clay can be understood at least in three different ways. First, according to Finnish soil classification system, clay is soil material, which passing percentage of 0.002 mm sieve is over 30 (Korhonen et al. 1974, p. 13). Clay is also name of a fraction of soil material passing 0.002 mm sieve. Thirdly, clay is a name of certain minerals found on soils. Clay material usually consist of both clay and non-clay minerals. (Mitchell 1976, p.24)

Behavior of coarse-grained soil types (e.g. sand and gravel) is mainly controlled by grain size, particle size distribution, particle shape, and surface texture. On the other hand, clay particles, with small particle size and high specific surface area, are physico-chemically active. This makes them to interact with each other, pore water, and dissolved ions in pore water. All of these have effects on behavior of clayey soils. (Mitchell 1976, p. 24) In the next chapters, building blocks of clays (minerals, pore water and dissolved ions) are presented.

2.1 Clay and nonclay minerals

Clay minerals are part of a mineral group called phyllosilicates, which contains also other minerals. The structure of the clay minerals consists of two different basic units that are called silica tetrahedron and aluminum or magnesium octahedron sheets. Structure of those sheets are shown in Figures 1 and 2, respectively.

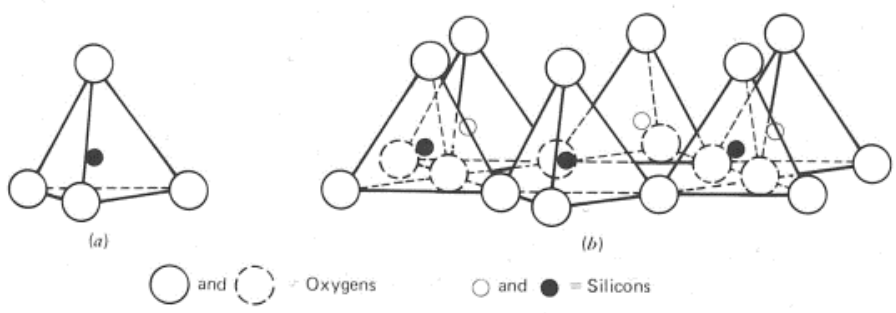

Figure 1. *Structure of silica tetrahedron sheet (Mitchell 1976, p. 29).*

Silica tetrahedron sheet consists of tetrahedrons with four oxygen anions in the corners and one silicon cation in the middle. Three oxygen anions, forming a base of the tetrahedron, are common with three other tetrahedrons next to them. Shared oxygens form a plane with hexagonal symmetry. The fourth oxygen anion belongs to only one tetrahedron at the time, and all of them are pointing to the same direction away from the plane. (Mitchell 1976, p. 29; van Olphen 1977, p. 58)

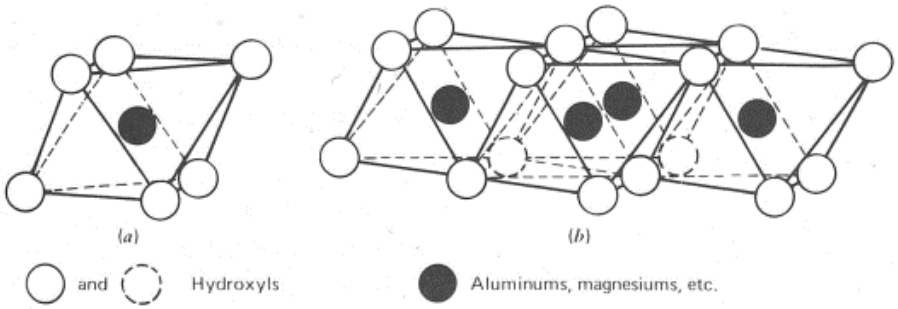

Figure 2. *Structure of octahedron sheet (Mitchell 1976, p. 30).*

Octahedron sheet consists of six oxygen anions or hydroxyl groups, forming an octahedron around aluminum or magnesium cation. Oxygens or hydroxyls compose two parallel planes around cation. With trivalent aluminum cation, only 2/3 of possible cation places are filled, and the sheet is called dioctahedral. In case of divalent magnesium, all places are filled, and the sheet is called trioctahedral. Sheets are also called gibbsite and brucite, respectively. (Mitchell 1976, p. 30)

In most cases, the usual cations in the tetrahedral and octahedral sheets substitutes for others during formation of mineral. Typical substitutes are aluminum, magnesium, and ferrous iron (Fe^{2+}). This phenomenon is isomorphous substitution, and it has a great influence on behavior of the minerals as will be discussed later. Typically isomorphous substitution occurs from higher to lower valence cation, which leaves excess electrons to the sheet and causes negative net charge on the sheet and eventually to the mineral itself. This negative net charge is balanced with some cations around the sheet. These are called exchangeable cations since they can change to another if the environment around the mineral changes. Amount of the exchangeable cations can be measured and the unit of that is meqv/100 g of dry sample. (Mitchell 1976, p. 31-32)

In clay minerals, above described sheets form layers with different compositions and thicknesses. These layers are called unit cells of minerals. Minerals compose of these unit cells stacked together with some charge balancing cations between them. In the unit cells, some oxygen anions are common giving strong bond between the sheets. Based on composition of unit cells, clay minerals can be divided into groups of similar properties shown in Table 1. Composition of the unit cell of a certain group can be described with notation for example 2:1. This means that unit cell contains two tetrahedral sheets and one octahedral sheet. In addition, inter-layer bonding is an important factor influencing properties of minerals. Due to that, it is used for classification. Minerals of the same group differs from one another by octahedral sheet (gibbsite or brucitite), cations taking part to isomorphous substitution, and the degree of that. (van Olphen 1977, p. 59-76)

Table 1. *Clay mineral groups and some properties (Mitchell 1976, p. 33-43).*

Name	Composition	Cation exchange capasity (meqv/100 g)	Interlayer bonding	Bond strength
Kaolinites	1:1	3–15	Van der Waals forces and hydrogen bonds.	Sufficiently strong
Smectites	2:1	80–150	Van der Waals forces and ionic bonds. Water molecules between layers.	Very weak
Illites	2:1	10–40	Potassium cation bonds. No water molecules.	Very strong
Vermiculites	2:1	100–150	Ionic bonds. Water molecules between layers	Weak
Chlorites	2:1:1	10–40	Octahedral sheet.	Very strong.
Mixed-layer clays	Varies	varies	varies	varies

Unit cells of kaolinite group minerals compose of one tetrahedral and one octahedral sheet stacked together. Tips of the tetrahedral sheet point towards the center of the unit cell and are common with octahedral sheet. Other anions in the octahedral sheet are hydroxyls, and those locate under hexagonal holes of the tetrahedral sheet. Structure of kaolinite can be seen from Figure 3. In kaolinite group minerals, interlayer bonding is quite strong and consists mainly of van der Waals forces and hydrogen bonds. The cation exchange capacity of the kaolinite group minerals is quite low (3–40 meq/100 g). This can be explained by low degree of isomorphous substitution in tetrahedral and octahedral sheets. Due to small inter layer spacing and the type of inter layer bonding, the exchangeable cations are assumed to locate on outside surfaces of the particles as well as on broken bonds around edges of the particles. (Mitchell 1976, p. 33-36; van Olphen 1977, p. 69-70)

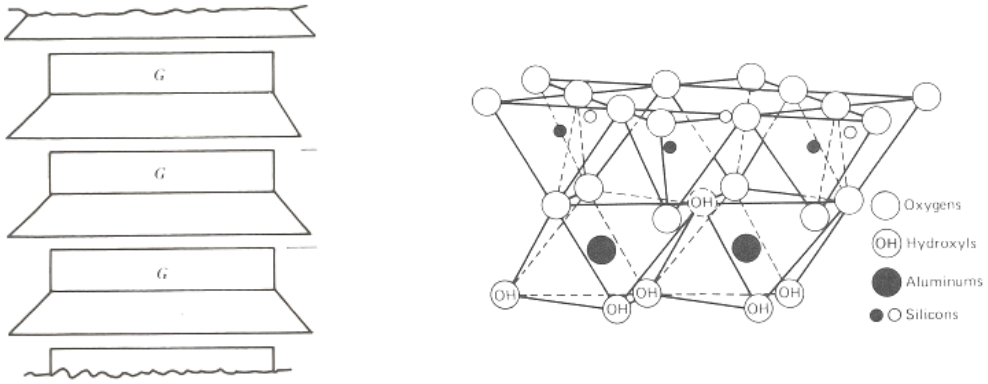

Figure 3. *Illustration of kaolinite structure and its unit cell (Mitchell 1976, p. 34).*

Smectites are 2:1 minerals composing of two tetrahedral and one octahedral sheets. Tips of the tetrahedral sheets point to the center of the unit cell and are shared with the octahedral sheet. Other anions of the octahedral sheets are hydroxyl groups. Those locate on hexagonal spaces formed by oxygens of the tetrahedral sheet base. Illustration of one of the smectite group minerals (montmorillonite) can be seen in Figure 4. Interlayer bonding is mainly van der Waals forces and ionic bonds between negatively charged unit cells and balancing cations. These bonds are remarkably weaker than in the kaolinite group and can break up easily. Due to that, when the smectite group minerals are exposed to water, the water molecules can penetrate between the unit cells causing so-called interlayer swelling of the mineral. In addition, smectites can swell even more due to osmotic swelling. Cation exchange capacity of the smectite minerals is in range of 80 – 150 meq/100 g, and it is caused by high degree of isomorphous substitution. Specific surface area of the smectite minerals is also very high because of their tendency to disperse into flakes of one unit cell thick. (Mitchell 1976, p. 36-38; van Olphen 1977, p. 64-68)

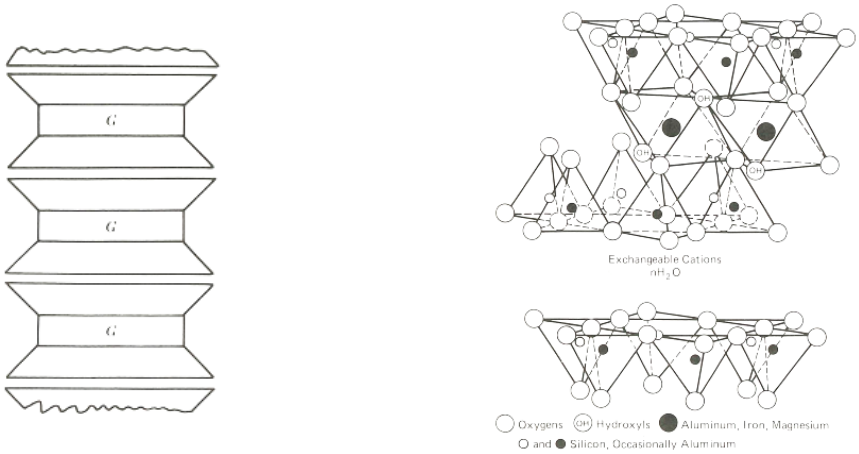

Figure 4. *Illustration of smectite group (montmorillonite) mineral structure and its unit cell (Mitchell 1976, p. 37).*

Another 2:1 type minerals are illites. Unit cells of illites consists of two tetrahedral and one octahedral sheets with same kind of structure as in the smectite minerals. Even though, illites and smectites are very similar, distinguishing factor between them is that illites will not swell when exposed to water. Structure of the illite is similar to the muscovite mica. Due to that, illite is sometimes called as hydrous mica. Schematic illustration of the muscovite mica/illite unit cell is shown in Figure 5 and structure in Figure 6. Isomorphous substitution of the illite minerals occurs mostly in tetrahedral sheet with one aluminum to silica substitution in every fourth silica anions and with some degree in octahedral sheet. Net negative charge, caused by isomorphous substitution, is compensated with potassium cations between the unit cells. Potassium cations fit snugly in the holes formed by anions in the tetrahedral sheet base causing strong bond between the unit cells. Because of the strong inter-layer bonding, illite minerals will not swell in water. This makes balancing potassium cations also non-exchangeable causing low cation exchange capacity of illites (10–40 meq/100 g) since only cations on the mineral edges are exchangeable. (Mitchell 1976, p. 39-40)

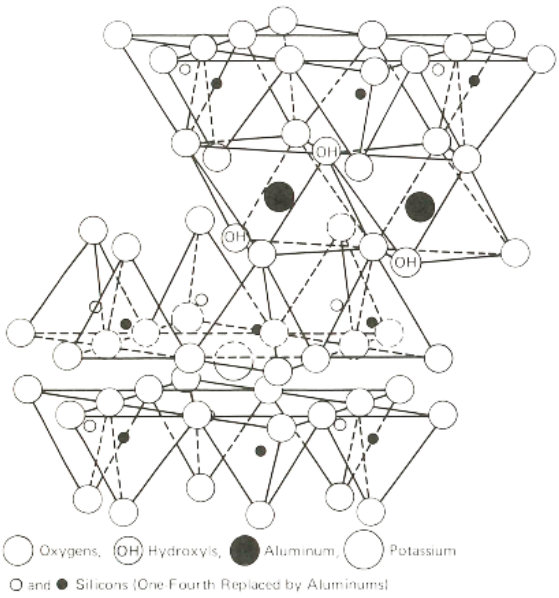

Figure 5. *Structure of muscovite mica unit cell (Mitchell 1976, p. 40).*

Another mica-like 2:1 mineral is vermiculite that contains water layers with different molecular thicknesses between the unit cells. Figure 6 illustrates structure of the vermiculite. The water layer thickness is depending on cations compensating the charge deficiency. For example with divalent magnesium and calcium cations, the water layer is two molecules thick. In vermiculites, the charge compensating cations between the unit cells are exchangeable causing higher cation exchange capacities (100–150 meq/100 g) than in illites. (Mitchell 1976, p. 39-42; van Olphen 1977, p. 68-69)

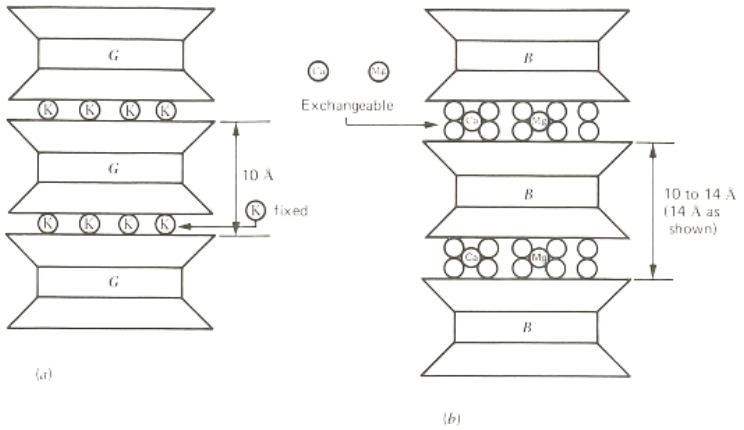

Figure 6. *Structures of a) illite and b) vermiculite (Mitchell 1976, p. 40).*

Fifth kind of clay minerals group is chlorites. Chlorites consists of 2:1 structure similar to the smectite and illite group minerals. In Figure 7, structure of chlorite is shown. The difference between chlorites and other 2:1 minerals is that the structure between unit cells compensating the charge deficiency is brucite type octahedral sheet. In that, some of the Mg cations are replaced with Al cations causing net positive charge of the layer. Since the compensating cations locate in brucite layer, they are fixed yielding low cation exchange capacities of chlorites. (Mitchell 1976, p. 42; van Olphen 1977, p. 70-71)

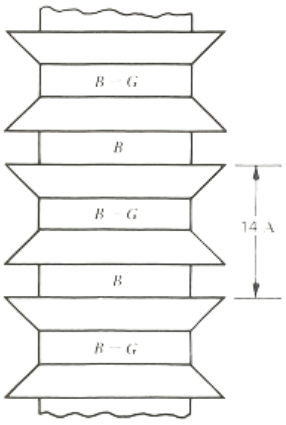

Figure 7. *Structure of chlorite (Mitchell 1976, p. 42)*

Since the structure of the minerals discussed above is so similar, it is possible to find particles with more than one mineral structure. This is called interstratification, and clays composing of these particles are named mixed layer clays. (Mitchell 1976, p. 43; van Olphen 1977, p. 71)

The sheet structure of previously mentioned minerals is not the only one found in clays. Some minerals compose of silica double chains, or they do not have clear structure at all (allophones). In addition, most clays contain also colloidal oxides. (Mitchell 1976, p. 42-43)

As a soil type, clays do not compose totally of clay minerals, but also non clay minerals in small particle size. As mentioned before, soil containing 30 % clay fraction can be called clay (Korhonen et al. 1974, p. 30). Even in clay fraction, up to 25 % of the minerals can be defined as nonclay ones (Soveri & Kauranne 1983, p. 61). Most of clays silt and plausible sand fraction compose of nonclay minerals (Soveri & Kauranne 1983, p. 61). In these coarser fractions, the most abundant mineral is quartz and other plausible minerals are feldspar and mica (Mitchell 1976, p. 25; Soveri & Kauranne 1983, p. 61).

2.2 Clay-electrolyte system

As mentioned before, since the clay particles are so small and their specific surface area is high, they interact with each other and pore water. The negative net charge caused by isomorphous substitution, causes interaction with clay particles and dissolved ions in pore water.

Isomorphous substitution caused net negative charge is compensated by positive ions attached to the particle surface. When placed to water, compensating cations tend to diffuse away from the particle surface due to lower concentration of the surrounding water. Still, the cations are affected by electrostatic force caused by opposite charge of the clay particle. These two oppositional affecting forces cause atmospheric distribution of cations on the particle surface. This distribution is called diffusion double layer (DDL). Near particle surface, concentration of cations is very high and diminishes as distance increases. In contrast, concentration of anions is very low near the particle surface and increases as distance increases. The ion concentration distribution is illustrated in Figure 8. Curves with plain and apostrophe symbols describe situations with low and high electrolyte concentration, respectively. Curves A–D and A'–D' show cation concentration as well as C–D and C'–D' anion concentration. As it can be seen from Figure 8, the cation concentration is all the way higher in the high electrolyte concentration situation. Although, with high electrolytic concentration the cation concentration decreases faster to the bulk concentration of the pore water as the distance from the particle surface increases. (van Olphen 1977, p. 29-35)

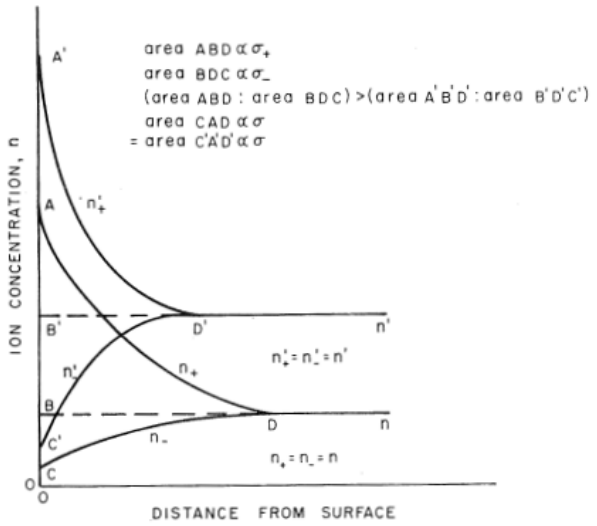

Figure 8. *Ion concentration distribution in diffusion double layer around clay particle. (van Olphen 1977, p. 32)*

Since the surface charge of clay mineral is determined by imperfections in the crystal lattice, it remains constant with altering pore water electrolytic concentration. Because of that, charges of the DDLs, determined by areas C'-A'-D' and C-A-D in Figure 8, are equal. In contrast, the electric-potential of the DDL on the particle surface decreases as the electrolytic concentration of the pore water increases. Due to that, it can be said that the DDL compresses towards the particle surface. The effect of the electrolyte concentration on the DDLs electric potential distribution is illustrated in Figure 9. (van Olphen 1977, 29-35)

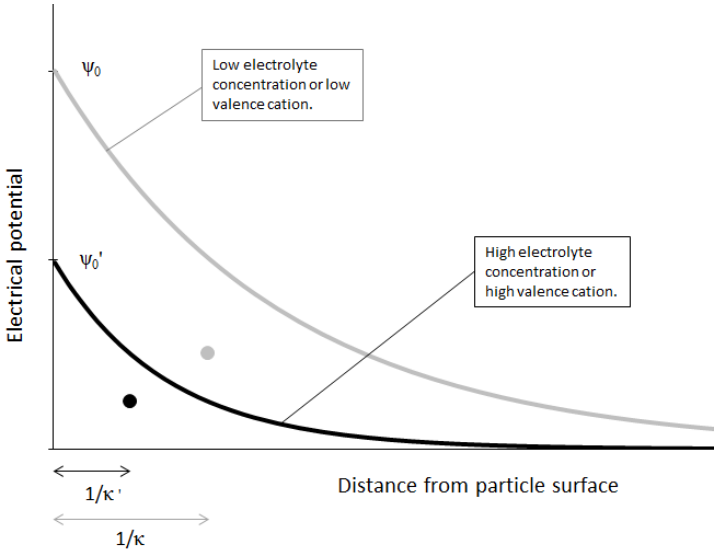

Figure 9. *Electric potential distribution of the DDL with two different pore water electrolytic concentrations or two different valence cations (adapted from Helle 2017, p. 12).*

Thickness of DDL ($1/\kappa$) is determined by a distance of potential distributions center of gravity from particle surface as illustrated in Figure 9. Due to that, the thickness of the DDL decreases with increasing electrolytic concentration. This has a great impact on inter particle forces and clay fabric as will be discussed on subchapter 2.3. Valence of cations on the DDL have similar effect on the potential distribution as the concentration of them. With higher valence cations, the DDL compresses towards the particle surface. The thickness of the DDL plays major role in inter particle behavior of clays. (Helle 2017)

Although flat surfaces of clay particles carry net negative charge, broken edges of the clay particles can act as negative or positive charged surfaces depending on the environment. That is because, on the edges of the particles, aluminum, magnesium or silicon atoms are exposed to the pore water and its ions causing metallic colloidal interaction between those. Surface charge of metallic colloids is determined by potential determining ions that change along with the electrolyte solution. The charge change in the edge DDL is determined mainly by pH of the solution. Especially, DDL of colloidal alumina is sensitive to change in the pH. A possibility of the positively charged DDL plays major role in flocculation process during sedimentation of clay. (van Olphen 1977, p. 93-95)

2.3 Clay fabric

Fabric of clay (soil type) can be defined in different scales starting from interlayer connection of individual unit cells of clay minerals, discussed in previous chapters, all the way to arrangement and compaction of the coarser silt or sand particles. In this chapter the concentration is in fabric that composes of interaction between individual clay particles.

According to van Olphen (1977) association of clay particles can be firstly aggregated or dispersed. This means that unit cells can be stacked together to larger particles (face-to-face flocculation) or those can act as individual particles. Secondly, the fabric can be flocculated or deflocculated meaning that the clay particles (aggregated or dispersed) can connect with each other. Forms of flocculation are edge-to-face and edge-to-edge. All these forms are illustrated in Figure 10. Different particle associations give differently behaving clay. With very open pore space structure (edge-to-face or edge-to-edge), the clay becomes compressible and high in water content.

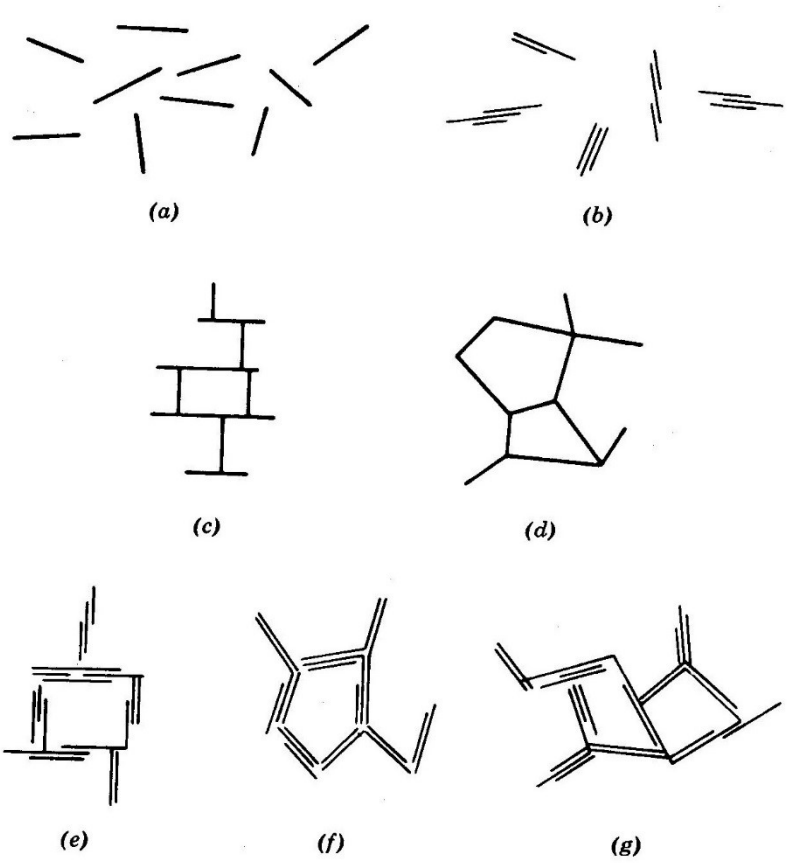

Figure 10. *Flocculation modes of clay particles (van Olphen 1977).*

Even though, the basic nature of clay particles is defined by small size of particles and chemical composition of minerals, the fabric generation is controlled mainly by the composition of pore water. With (practically) dilute pore water solutions, the forming clay fabric is not defined by edge-to-face or edge-to-edge house of cards structure. This is due that, the low ion concentration expands the DDLs so large that electrical and van der Walls forces, acting between clay particle faces and edges, are overcome by repulsive forces of the overlapping DDLs. If the ionic concentration of pore water increases, the DDLs compress and attractive forces become dominant. This enables edge-to-face or edge-to-edge flocculation, forming house of cards structure with high void ratio and natural water content. (van Olphen 1977, p. 95-98)

As a conclusion, clays are chemically and electrically active compounds of soils. These properties are caused by small size of clay particles as well as electrical charge due to isomorphous substitution. In addition, these same properties effect on clay structure and its mechanical behavior.

3. CLAY FORMATION

In this chapter, formation of soils and especially clays is discussed. Since focus of this thesis is in the Finnish clays that have mainly formed through a sedimentation process, other formation modes are described just shortly.

3.1 Geologic cycle

Soil formation is a part of the geologic cycle illustrated in Figure 11. Molten magma rises up near the Earth surface due to crustal movements. When temperature of the magma reaches low enough values (s. c. crystallization temperature), crystallization of rock forming minerals starts. If cooling continues slowly, the crystals form better and become large. On the other hand, very fast cooling, for example during a volcanic eruption, prevents the formation of a clear mineral structure, and the result rock is amorphous. After the crystallization, the formed rock reaches the Earth surface and is exposed to the atmosphere and/or the hydrosphere.

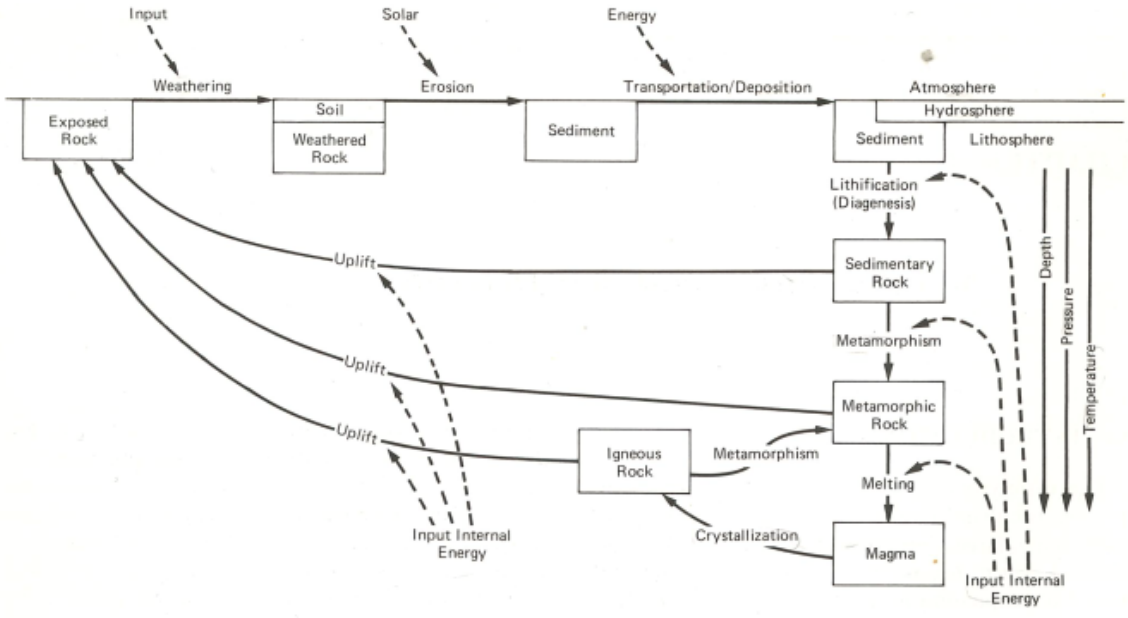

Figure 11. *Geologic cycle of rock and soil (Mitchell 1976, p. 48).*

Previously mentioned exposion, starts a weathering process of rock. The weathering composes of physical, chemical and biological parts, each of which can act on rock simultaneously. Weathering breaks down and alters formed rock, and, in some point, weathered rock becomes soil. Clear difference between rock and soil cannot be made. (Mitchell 1976, p. 47-83)

Further, weathered rock, or soil, can expose to erosion. It means detaching of weathered material due to different flows (air, water, ice). Depending on the force or speed of the eroding flow, particles of different sizes can move with it. (Mitchell 1976, p. 47-83)

When the force of the eroding flow decreases, the particles start to settle and form sediment. All different size particles can be settled in same place, or they can be sorted out by the eroding flow. This has a critical effect on behavior of forming sediment. (Mitchell 1976, p. 47-83)

Due to the effects of the atmosphere and the hydrosphere, the sediments can form sedimentary rocks. Those can sink back below the Earth surface and molt to magma. After that, the geological cycle starts over. All the processes described here can happen multiple times, or some might not happen at all. (Mitchell 1976, p. 47–83)

On the next chapter, sedimentation part of the geologic cycle is described in greater detail. Also after sedimentation processes are described.

3.2 Sedimentation process

Sedimentation can be divided in three separate parts: erosion, transportation, and deposition. Erosion means detaching soil particles by some force, transportation is moving the particles to a new area, and deposition means settlement of the particles to the new area.

Erosion happens due to flows of fluid (air, water or ice) that picks up soil or rock particles with them. On steep areas, gravitational forces can also drive erosion. Erosion can happen only if the eroding force acting on the particle overcomes the stabilizing forces of it. This includes forces caused by gravitation, cohesion and friction. The main effector of fluid flows capability to erode soil is its velocity. Particles stay in motion as long as the velocity of the flow decreases under certain level called settling velocity. This is also the thing with erosion. With low enough velocity, particles will not detach and erosion cannot happen. Compared to transportation, the erosion flow velocity needs to be higher, since more forces act on the particles attached to each other than on the separate particles moving with the flow. (Mitchell 1976, p. 47–83)

Similar factors effect on transportation of the particles as on erosion. As discussed above, a lower velocity of fluid is needed for transportation as for erosion. When erosion is affected by the velocity of fluid on the boundaries of it and soil, transportation is affected by the average speed of fluid. Also the eroding agent effects on the degree of the transportation, for example flow of ice needs to be much slower than wind to erode and transport similar particles. Due to that, it is actually energy of the flow that controls both phenomena. Figure 12 illustrates velocities of air and water needed to transport and erode different size particles. Above the straight lines, the particles are transported. If the velocity exceeds also the curved lines, erosion can happen. Figure 12 also illustrates the

difference between different eroding agents. With same velocities, water can erode and transport much larger particles than air (wind). (Mitchell 1976, p. 47–83)

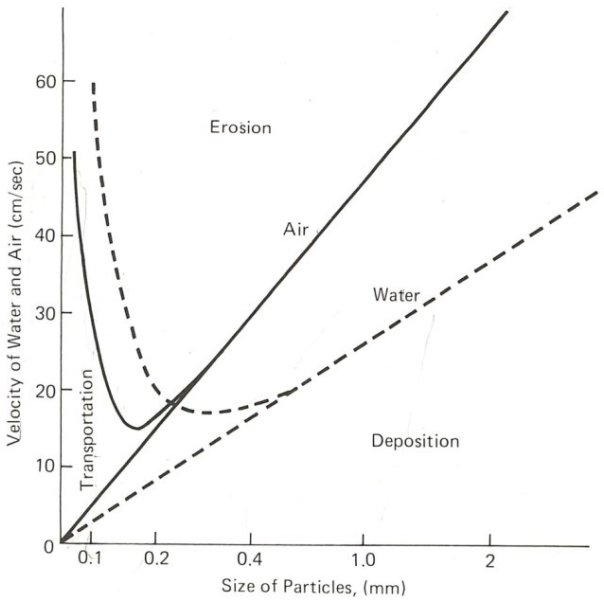

Figure 12. *Erosion and transportation velocities of air and water flows for different particle sizes (Mitchell 1976, p. 62).*

Transportation effects also on the properties of sediments. First, transportation sorts out material that flows with it. This can happen on local or progressive basis. Local sorting creates lenses of different sediment properties inside the sediment deposits. Progressive sorting effects on the whole deposit creating progressive change in the grainsize distribution with the direction of the flow. This happens due to different sizes of the particles, but also the shape of them effects on sorting. For example, spherical particles of the same size settle faster than plate or needle like (clay) particles. Secondly, transportation effects on surface structure of the flowing material. This is distinguishing particularly for wind-transported sands. Contrary, the clay particle surfaces are not affected significantly by transportation. (Mitchell 1976, p. 47–83)

Deposition starts when the velocity of the transporting flow decreases under the settlement velocity. This can happen due to actual decrease in the velocity or changes in the matter flowing with the fluid. For example, changes in temperature or in chemical conditions can effect on the flocculation tendency of colloids increasing particle size and the settlement velocity. Deposition can also be cyclic, which can be seen, for example, in varved clay deposits. Cycles of these deposits can vary from annual changes to changes of climate through thousands of years. Varved clay is a typical formation that illustrates changes in the glacial deposition environment in annual basis. A pale siltier layer forms in summer when meltwater flow is faster, and a darker clayey layer settles in winter when the flow is almost stopped. (Mitchell 1976, p. 47–83)

3.3 Effect of the sedimentation environment

Sedimentation environment can have significant effects on the sediment properties. According to Mitchell (1976), sedimentation environments can be divided into three large groups with several subgroups. The sedimentation environments are continental, marine and mixed environment. The continental environment consists of different environments found above sea level, for example, glacial and lacustrine (lake) deposits. The marine environment can be divided in to three parts, which are continental shelf, continental slope and deep-sea areas. Mixed environment exists between marine and continental environments. It can be found in shores between tidal limits and from deltas near river mouths. All of these environments can produce several types of sediments depending on specific sedimentation environment. In this subchapter glacial sediment deposits are described closely.

Flowing ice has the greatest eroding and transporting energy of all. Everything from house size erratic boulders to clay colloids move along, and there is no upper bound for size of particles it can move. Ice deposited material is typically moraine and its modifications. Moraine consists of different size particles with angular shapes. Bottom moraine, deposited under the flowing ice, is usually more fine-grained and denser than other forms of moraine. Glacio-fluvial deposits consist of sorted gravel and sand. Sorting occurs due to the melt water flows of ice. Glacial and post-glacial lake and marine sediments consists of fine-grained silts and clays with different structures. Grading of material is poor in channel deposits. On the other hand, in lake and sea floor deposits grading is evident, and in some deposits varved clay can be found.

Also, differences in salinity and pH on sedimentation environment effects on the sediment properties. As discussed in chapter 2, a high electrolytic concentrations tends to flocculate colloidal clay particles while in low concentrations they prefer to disperse. Flocculated structure is called symmict, and dispersed layer structure is called diatactic. When sedimentation happens very far from melting ice and velocity of transporting flow is very low, symmict structure can occur even in a low saline environment. (Mitchell 1976, p. 47–83; Salonen 2002, p. 53–54)

3.4 After sedimentation processes

After sedimentation, formed deposit is not on static state, but several factors effect on it. First, consolidation, driven by overburden, takes place after the sedimentation. Depending on thickness of the deposit and the permeability of the soil, primary consolidation may take up to hundreds of years. In addition, creep or secondary consolidation effects also on the deposit increasing effects of the primary consolidation. Due to consolidation, void ratio of the soil decreases increasing strength and stiffness and decreasing permeability. Creep effects can also cause apparent over consolidation. (Mitchell 1976, p. 47–83)

Another source of the increasing apparent over consolidation is cementation. It means forming of bonds between soil particles due to chemical reactions. Usually found cementation agents are carbonates, metallic cations and organic compounds. Cementation also effects on stress-strain behavior and sensitivity of the soil and is also one source of a true cohesion. (Mitchell 1976)

Authigenesis means formation of new minerals in place. This can take place in a deposit after sedimentation. For example, smectite can turn to illite due to overburden of thousands of meters that compresses water layers off between the unit cells. Chemical changes in environment also drives authigenesis. (Mitchell 1976, p. 47–83)

Percolation of ground water also effects on a deposit. If fresh ground water percolates through the deposit settled in a marine environment, it dramatically changes chemical structure of the pore water. Dilution of the pore water expands DDLs of clay colloids increasing the repulsive forces between them. This is proved to be the main cause of the quick clay formation (Bjerrum 1954). (Mitchell 1976)

In addition to the above mentioned, top parts of deposits can be affected by some other factors. Weathering, similar to freshly exposed rock formations, can take place also in the sedimentary deposits. For example, oxidation and change of exchangeable cations can have significant effects on the sediments behavior. Biological factors can also effect on the deposit. For example trees and other plants can create significant suction to the deposit causing decrease of water content and increase of consolidation. For the top most part of the deposit, lying above ground water table, a dry crust formation can occur. It comprises of several factors related to weathering and authigenesis. Distinguishing properties of the dry crusts are high strength, low water content and fissured structure (due to shrinking) (Ringesten 1988). (Mitchell 1976, p. 47–83)

In addition to the all of above mentioned, deposit can face erosion and re-deposition to some other sedimentation area. This can happen due to changed climatic or chemical environment. Also changes in river channels and isostatic uplift can affect on erosion of sediments. (Mitchell 1976, p. 47–83)

As a conclusion, clays are formed as a part of the geologic cycle. Clays are also mainly formed through a sedimentation process. Main factors effecting on clay deposits are eroding and transporting flows and deposition environment. Chemical composition and temperature of the environment seems to effect mostly to depositing clay. After sedimentation, several factors effect on the deposit changing its structure, mineralogical composition and stress state.

4. SEDIMENTATION ENVIRONMENT AND GEOTECHNICAL PROPERTIES OF FINNISH CLAYS

Typical for Finnish soil and rock is an old Precambrian bedrock and a thin, young quaternary soil cover (Korsman & Koistinen 1998; Salonen et al. 2002). All of the Finnish soil deposits are formed in the Quaternary period and most of them during and after the last glacial period (Salonen et al. 2002).

4.1 Weichselian glacier in Finland

2.5 million years ago, geological period changed from the Tertiary to the Quaternary. Distinguishing features of the Quaternary period are fluctuating climate conditions with glaciers and inter-glaciers. Previous glaciers from oldest to youngest are Elster, Saale and Weichselian, and the last interglacial, before Weichselian, is called Eemian. Most of Finnish soils are formed during the Weichselian glacier and after it. Even though, signs of the Saale glaciation and the Eemian inter-glacial can be seen in Finnish soils, but the Elster glaciation based formations cannot be found. (Salonen et al. 2002, p. 14-17)

The Weichselian glacier can be divided in to three parts, Early, Middle and Late Weichselian. The Early Weichselian begun after the Eemian inter-glacial about 115,000 years ago. It comprises of two separate glaciers both which melted before begin of the Middle Weichselian. (Salonen et al. 2002, p. 18-20)

The Middle Wiechselian started about 85,000 years ago after the second warmer phase of Early Weichselian. Also during that time, reach of the continental ice sheet altered largely, and Finland is proposed to be ice-free on some period during the Middle Weichselian. (Salonen et al. 2002, p. 18-20)

The Late Weichselian started about 25,000 years ago. It is the coldest period of the whole Weicselian glacier and the continental ice sheet reached southern parts of Denmark, Germany and Poland about 17,000 years ago. After its maximum, the continental ice sheet started to recess due to warming of the climate. Recess did not happened evenly, but several stops and faster recessions occurred during it. The Weichselian glacier is assumed to end about 11,500 years ago and the present inter-glacial is called Flander. (Salonen et al. 2002, p. 13-20)

4.2 Phases of the Baltic Sea basin after Weichselian

The fine-grained sediments of Finland are mostly formed after Weichselian glacier in different sedimentation environments provided by the Baltic Sea. Soil and rock material was eroded and transported by the continental ice sheet. The eroded material was furtherly transported and sorted by the meltwater flows and settled to bottom of the Baltic Sea. Major changes in the Baltic Sea history took place between 11,500–8000 years ago. Figure 13 illustrates shorelines of the Baltic Sea during its glacial and post-glacial phases. (Gardemeister 1975, p. 10-11; Salonen et al. 2002, p. 13-14)

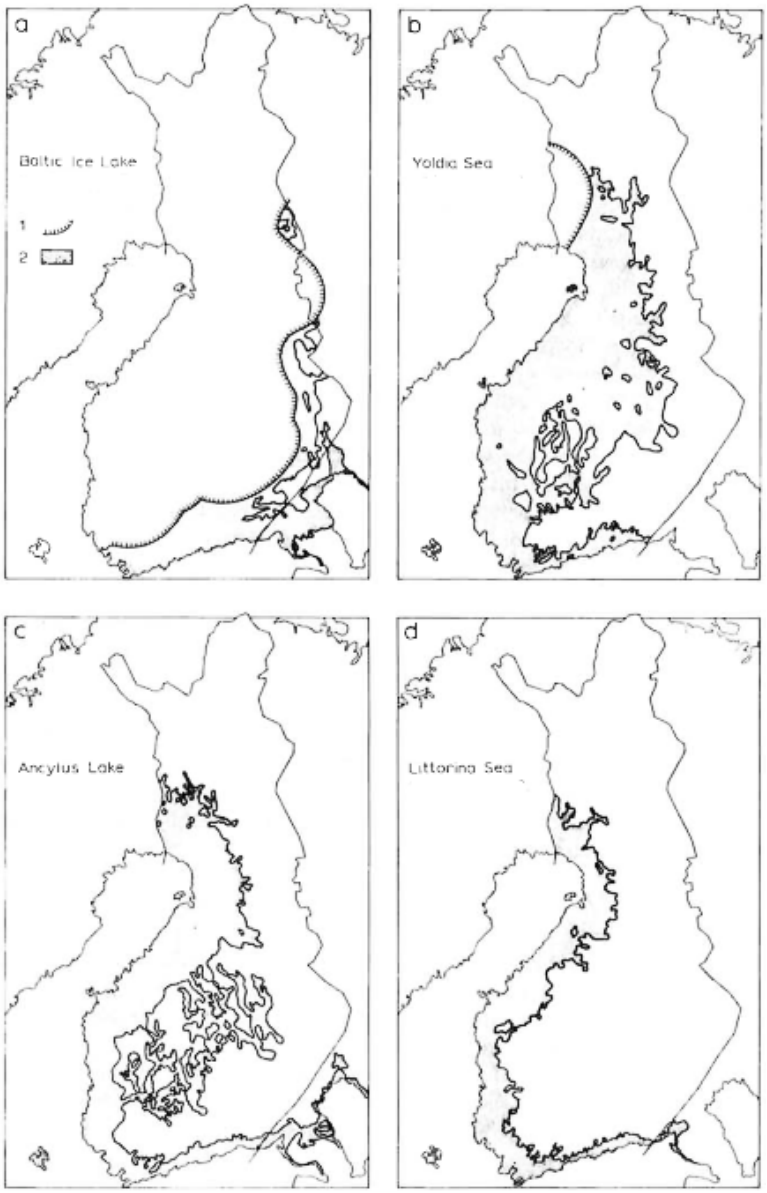

Figure 13. *Phases of the Baltic Sea basin (Gardemeister 1975, p. 11).*

First phase of the Baltic Sea, in the last moments of Weichselian glacier and after it, is called Baltic Ice Lake. It formed behind the recessing continental ice sheet to the sunken depression of bedrock formed by the enormous ice masses. Water of the lake was fresh, and as the climate was still cold, production of organic matter was low. End of Baltic Ice

Lake came about 11,500 years ago when a connection to the Atlantic Ocean opened due to recessing ice. (Salonen et al. 2002, p. 26)

While the connection to the Atlantic Ocean opened, water level of the Baltic Sea basin decreased dramatically. This started a new phase called the Yoldia Sea. In the early stages of the Yoldia Sea, the water was still fresh due to heavy flow to the Atlantic Ocean and melt water flows from the continental ice sheet. Salt water started to flow into the Yoldia Sea 200 years after the connection opened. Even though, salinity was only moderate, and water of the Yoldia Sea could be classified as brackish. (Salonen et al. 2002, p. 26)

Next phase of the Baltic Sea basin, called Ancylus Lake, started 10,800 years ago when the connection to the Atlantic Ocean closed due to isostatic uplift. The water level raised intensively, and water of Ancylus Lake was fresh. (Salonen et al. 2002, p. 28)

Last phase of the Baltic Sea basin started when a new channel opened to the Atlantic Ocean due to rise of the Ancylus Lake water level. This phase is called the Litorina Sea, and it started about 10,000 years ago. Flow of saline water started a thousand years after the connection opened, and the main basin of the Baltic Sea filled with saline water about 8000 years ago. During the Litorina Sea phase, the continental ice sheet was almost totally melted and the climate was very warm. Salinity of the Litorina Sea was around 6–8 ‰ and production of organic matter was higher than these days. The Litorina Sea phase ended around 5000 years ago, and a phase, known as the Limnea Sea, started. The present Baltic Sea is formed from the Limnea Sea during last 5000 years. (Salonen et al. 2002, p. 29-30)

4.3 Properties of fine-grained sediments in Finland

As discussed above, the Finnish fine-grained sediments are deposited mostly to the glacial and post-glacial Baltic Sea. Due to the isostatic uplift and changes in water level, the deposits are nowadays in dry land. Most of the fine-grained sediments are found in the coastal regions of Finland, which have been under water during some phases of the Baltic Sea. Some fine-grained lake and river deposits can be found from the inner parts of the country. Figure 14 illustrates a distribution of the clay deposits in southern and central parts of Finland. (Salonen et al. 2002, p. 53-55)

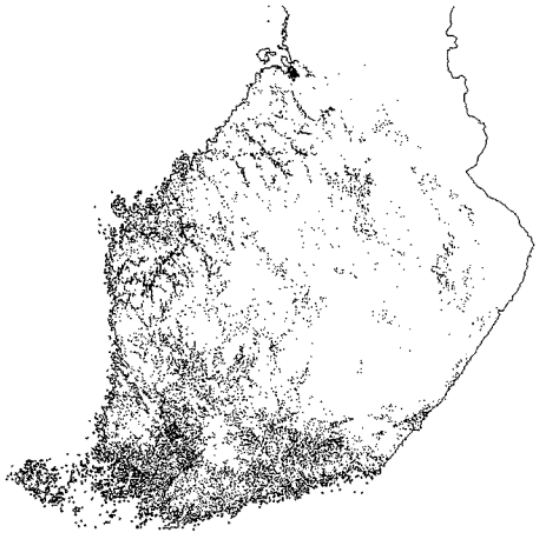

Figure 14. *Distribution of clays in southern and central parts of Finland (Salonen et al. 2002, p. 55)*

Gardemeister (1975) made an extensive research on the properties of the Finnish fine-grained sediments. He suggests that the origin of the sedimentary material of the Finnish fine-grained sediments is, at least in some extent, originated from the interglacial sediments. This is proven by pollen and mineralogical analysis made during the research. Most interglacial material is found from the varved clays of Baltic Ice Lake and Yoldia Sea sediments. Material of the post-glacial Ancylus and Litorina sediments are suggested to originate from previously eroded and re-sedimented glacial clays.

All over mineralogical composition of the Finnish fine-grained sediments is consistent and not significant differences can be found from different parts of country and sedimentation phases (Gardemeister 1975, p. 22-32). Coarse grains of the fine-grained material is mostly quartz and feldspar as most of the clay size fraction is composed of illite and chlorite. In the clay fraction some vermiculite can also be found (Gardemeister 1975, p. 22-32). Contrary to the findings of Gardemeister (1975), Soveri (1950) found the Finnish fine-grained sediments to compose mainly of mixed layer minerals and the amount of vermiculite was higher (Gardemeister 1975, p. 22-32). The difference between these findings could be that most of the samples of Soveri were taken from dry crust layer and right below it as the samples of Gardemeister came from deeper levels when the effect of weathering is smaller (Gardemeister 1975).

Gardemeister (1975) also proposes some fundamental properties of the fine-grained sediments of certain phase of the Baltic Sea. Some properties are very distinguishing for the certain sediment as others are in the same range for all the sediments.

Varved clay of Baltic Ice Lake has a clear varved structure and is high in silt and low in clay content. Sometimes the clay content is so low (under 30 %) that the soil type is not anymore clay but silt. Distinguishing feature is also a low organic content. Due to the

lower clay content, the Baltic Ice Lake sediments have lower average water content and plastic index than the other Finnish fine-grained sediments. (Gardemeister 1975)

The Yoldia and Ancylus sediments are very similar. Both have high clay and low organic content. Slight difference could be found in the average clay content, which is little bit higher for the Yoldia sediments. Structure is also very similar, symmictic with no clear varved structure. However, in the early Yoldia sediments slight varving can be seen. Even though, water of Ancylus Lake was fresh, the distance between the meltwater flows and the final deposition site is so long that no diatactic structure is found. Similarity between these sediments is so high that identifying of these sediments based on simple geotechnical tests is almost impossible. (Gardemeister 1975)

The Litorina sediments have highest salinities due to high salinity of the Baltic Sea basin during their deposition. In addition, also very low saline sediments of Litorina Sea phase can be found. This might be caused by leaching of pore water due to the isostatic uplift and rain water percolation, but also some river channel deposits can have low salinities due to the diluting effect of fresh water. Distinguishing feature of the Litorina sediments is high organic content. This is due to warmer climate compared to present, and high produce of organic matter caused by it. (Gardemeister 1975)

According to Gardemeister (1975). for the low organic content Baltic Ice Lake, Yoldia Sea and Ancylus Lake sediments. main factor affecting on geotechnical classification properties is clay content. While in case of the Litorina Sea sediments, main factor seems to be organic content. Some average values of the classification properties of the South Finland's fine-grained sediments are shown in Table 2.

Table 2. *Average classification properties of South Finlands fine-grained sediments (adapted from Kauranne et al. 1979, p. 158)*

Property	Sedimentational phase			
	Baltic Ice Lake	Yoldia Sea	Ancylus Lake	Litorina Sea
Clay content (%)	30 ± 25	70±15	65±15	55±20
Organic content (%)	0.5	1–1.5	1–1.5	2.5–8
Salinity (‰)	0.1–0.5	0.5–3	1–2	4–8
Water content (%)	40–60	70–120	70–80	120–150
Liquid limit (%)	40–60	60–90	70–90	90–160
Plasticity index	25–35	40–60	45–50	60–110
Sensitivity	8–12	7–20	8–12	7–12
Unit weight (kN/m^3)	15.6–17.7	13.7–15.6	14.7–16.7	12.8–14.7

As can be seen from the Table 2, many properties of the different sediments have values in a wide range, and many values overlap with each other making identification of specific sediment layers difficult. In addition, when taking into account also properties of

sediments from the different parts of Finland, the range of these parameters becomes even wider. However, taking into account for multiple parameters the identification might be possible. For example, clay with high salinity and organic content would indicate it to be Litorina sediment, while low clay, organic and salt contents indicates presence of a Baltic Ice Lake sediment.

As a conclusion, Finnish fine-grained sediments are formed mainly during and after the Weichselian glacier into the Baltic Sea. Different phases of the sea, caused by changes in environment and recessing continental ice, have formed different types of sediments. Some properties of these sediments are very distinguishing, and identification of a certain sediment layer can be done based on those.

5. ELECTRICAL CONDUCTIVITY OF SOILS

In this chapter principles of electrical conductivity of soils and especially clays is presented. First, general aspects of conductivity are gone through and after that modelling and measuring soil conductivity is discussed.

5.1 Electrical conductivity in general

Electrical conductivity is based on electric field in a medium caused by an outer electromotive force (e.m.f). This induces an electric current to the medium. Term σ that defines the relationship between the current density and the electric field is known as electrical conductivity of the medium. This relationship is called Ohms law and is shown in equation 4.1:

$$\bar{J} = \sigma \bar{E}, \tag{4.1}$$

where J is the electric current density, σ is the electrical conductivity of the medium and E is the electric field. Both J and E are vector quantities. Unit of the electrical conductivity is S/m (siemens/meter) The inverse of the conductivity is called resistivity, usually denoted by ρ, and is also used in soil investigation applications. (Peltoniemi 1988, p. 128-129)

The electrical conductivity phenomenon can be defined based on current transmitting charges. In metals and semiconductors, the transmitting charges are electrons and in electrolytic solutions ions. In soils, most of the electric current is transferred by ions in electrolytic solutions. (Peltoniemi 1988, p. 129-130) Conductivity is not an independent property of a specific material, since it changes along environment and measuring technique. For example, in metals conductivity decreases with increasing temperature, while in electrolytic solutions, conductivity increases with increasing temperature. This can be explained by the microstructure of the current transmitting charges. In metals thermal radiation of the electrons increases with temperature causing errors in the current transmission causing conductivity decrease. However, in electrolytic solutions a temperature increase improves mobility of the ions causing increasing conductivity.

5.2 Soil conductivity models

Since soil is a granular medium with solid particles and voids, a flow of electric current through it is a complex series of events. Even though this thesis treats only fully saturated soils making soil two-phased, effect of pore water chemistry along with colloidal effects of small clay particles adds complexity to the determination of conductivity.

In literature, basis of soil conductivity is usually the Archie's law (Archie 1942):

$$\sigma_a = \sigma_w n^{-m}, \tag{4.2}$$

where σ_a is apparent soil electrical conductivity, σ_w is pore water conductivity, n is porosity, and m is material dependent factor. Archie (1942) determines the law empirically based on electrical measurements of sedimentary rocks. He determines m varying between 1.8–2.0 for consolidated and cemented sands and being around 1.3 for unconsolidated sand. Since m seems to increase along with cementation, Archie names it to cementation index (Mohamed & Paleologos 2017, p. 501). Part of the Archie's law that defines the relation between the electrical conductivity of soil and its pore water is named formation factor F. The formation factor is determined by the equation $F=n^m$.

Even though the relation between the electrical conductivity of soil and its pore water described by the Archie's law is primarily empirical, Friedman (2005) presents several studies that gives a theoretical background for it. One of them is a two-phase model described by Maxwell (1881). Assumptions of the Maxwell model contains two phases with different electrical conductivities and volumetric fractions. Solid matrix of the model composes of spherical particles with electrical conductivity σ_s and volumetric fraction $f = 1-n$. Randomly arranged solid matrix is surrounded by substance with conductivity σ_w and volumetric fraction of n. With these assumptions the equation (4.3) describes the Maxwell model:

$$\frac{\sigma_a-\sigma_w}{\sigma_a+2\sigma_w} = f\frac{\sigma_s-\sigma_w}{\sigma_s+2\sigma_w}. \tag{4.3}$$

If the solid matrix is non-conductive ($\sigma_s = 0$), the equation gets form of (4.4):

$$\frac{\sigma_a}{\sigma_w} = \frac{2n}{3-n}. \tag{4.4}$$

Even though the Maxwell model demands several simplifications compared to a real soil matrix, it seems to predict electrical conductivities of several two-phase media as it can be seen from Figure 15. Nevertheless, simplifications of the Maxwell model over predicts the electrical conductivity in most cases.

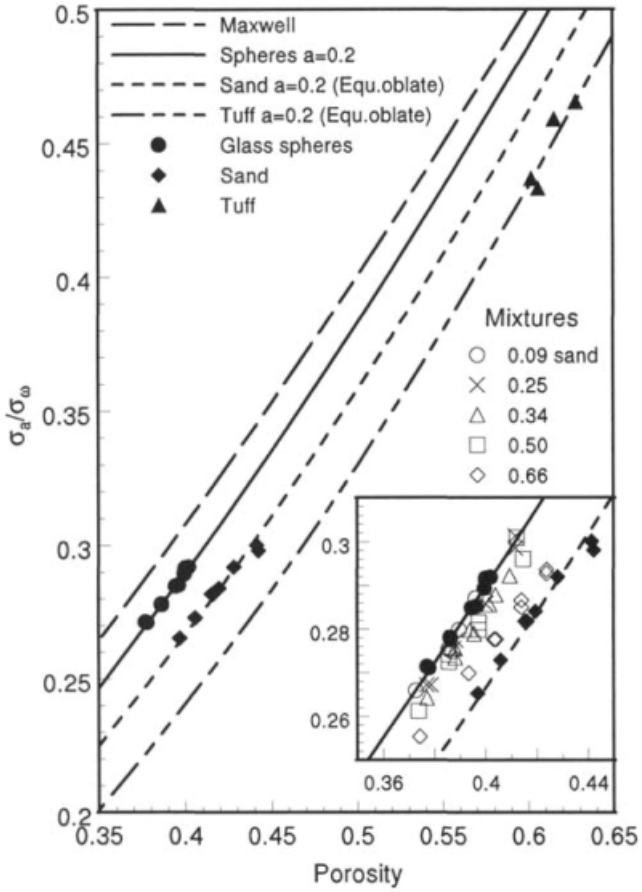

Figure 15. *Correlation between electrical conductivity normalized with pore water conductivity and porosity (Friedman & Robinson 2002, p. 7).*

Friedman (2005) also introduces a self-similar model developed by Sen et al. (1981). The model is developed to describe dielectric permittivity of a two-phase medium, but it can also model electrical conductivity of it. Model can be described by the Bruggeman's (1935) approximation (equation (4.5)):

$$\left(\frac{\sigma_s-\sigma_a}{\sigma_s-\sigma_w}\right)\left(\frac{\sigma_w}{\sigma_a}\right)^{1/3} = n, \tag{4.5}$$

which reduces to Archie's law in case of $\sigma_s = 0$. Cementation index equals in that case $m = 3/2$. Friedman (2005) assumes this relationship to be so fundamental that it is recommended to use for the determination of σ_w or n if no additional data is available.

Previous models assume that the electrical conductivity of pore water causes the electrical conductivity of soil directly, and no current flows though the solid matrix of soil (Fried-

man 2005, p. 56-57). This assumption can easily be made to a clean, coarse-grained material with non-conductive minerals or when pore water salinity is very high (around 400 mS/m) (Friedman 2005, p. 56-57). However, the situation is a bit different with soils including serious amounts of clay minerals and/or dilute pore water. As was discussed in chapter 2, small size of the clay mineral particles and their negative net charge causes colloidal effects. This influences on distribution of ions in pore water as DDL is formed. The DDL effects on conduction phenomenon and adds complexity to the relationship between electrical conductivity of soil and its pore water.

To take into account the effect of the DDL on electrical conductivity of clayey soils, Waxman & Smiths (1968) presents equation (4.6):

$$\sigma_a = \frac{1}{F^*}(\sigma_s + \sigma_w), \tag{4.6}$$

where F^* is formation factor analogical to Archie's law and σ_s and σ_w are conductivities caused by the exchangeable ions and the pore water respectively. For clean sands, conductivity of the exchangeable ions diminishes $\sigma_s = 0$ and formation factor becomes equal with the Archie's law $F^* = F$. To ensure the applicability of the equation (4.6) Waxman & Smiths (1968) assumes that the tortuous paths of current through the both conductors are same. However, this assumption is rejected later in the same article and more complex equation taking into account the mobility of the exchangeable ions is introduced.

Rhoades et al. (1976) introduces further development of a two-phase conductivity model of soils to take account for unsaturated soils also. Equation (4.7) describes the two-phase model of Rhoades et al.:

$$\sigma_a = \sigma_w \theta T + \sigma_s, \tag{4.7}$$

where θ is volumetric water content of soil and T is a transmission coefficient. The transmission coefficient T is described by equation (4.8):

$$T = a\theta + b, \tag{4.8}$$

where a and b are constants. As it can be seen from equations (4.7) and (4.8), the two-phase model of Rhoades et al. assumes the surface or DDL conductivity to be independent on the free pore water conductivity. On the other hand, the conductivity of the free pore water changes with the volumetric water content. This does not seem to be in line with DDL theories described in chapter 2.

Rhoades et al. (1976) made an experimental validation for their model and measured electrical conductivities of soils with different grain size distributions in several pore water conductivities and volumetric water contents. For the most clayey soil of their study (30 % clay and 30 % sand) they suggested the transmission constants a and b to be 2.134 and -0.245, respectively.

Mualem & Friedman (1991) developes a two-phase model for soil electrical conductivity by presenting equation (4.9) based on the previous studies (Dutt & Anderson 1964; Rhoades et al. 1976; Bolt 1979; Shainberg et al. 1980):

$$\sigma_a = \frac{\sigma_w}{F} + \sigma_s(\sigma_w), \tag{4.9}$$

where F is formation factor of the Archie's law and σ_s is surface conductivity. In equation (4.9) the soil conductivity composes of two conductivities acting parallel. First is free pore water conductivity similar to the Archie's law, and the other is a surface conductivity, which is a function of the pore water conductivity. The surface conductivity can be assumed to be consequence of ions acting on the DDL.

In the Mualem & Friedman two-phase model, effect of pore water conductivity to surface conductivity seems to be in line with the properties of DDL described in chapter 2. Since the negative net charge of the clay mineral colloid is caused by internal errors in the crystal lattice, the electric potential of the DDL changes along with the pore water concentration causing changes to its size and partly to the electrical conductivity of soil.

Rhoades et al. (1989) describes a soil conductivity model of three parallel conductors based on the findings of Sauer et al. (1955). The Rhoades et al. (1989) model accounts for a conductance through the free pore water, the soil particle surface (due to exchangeable cations), and the altering soil-pore water series coupled pathway. Figure 16 illustrates the three pathways of the model in a schematic and simplified form.

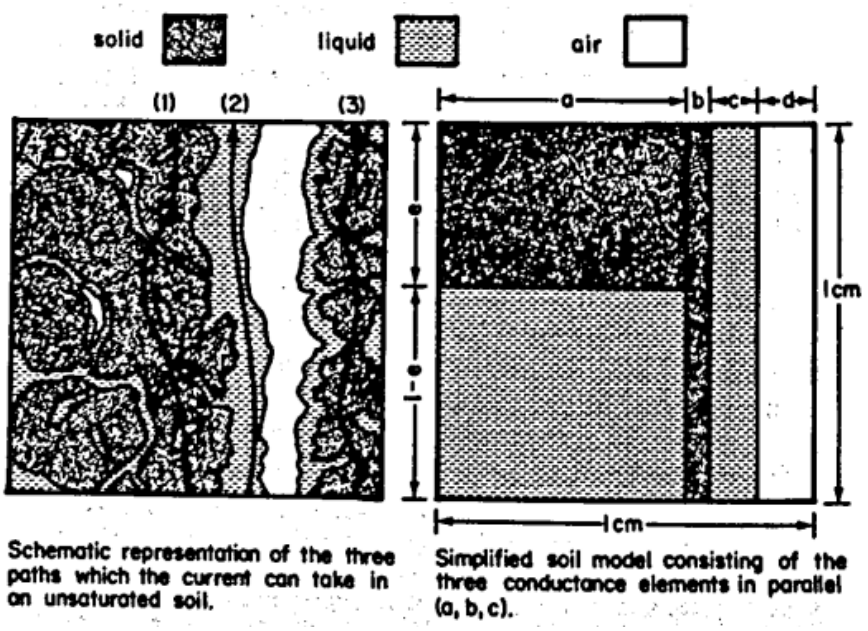

Figure 16. *Schematic and simplified illustrations of the three phase model (Rhoades et al. 1989, p. 434).*

As it can be seen from Figure 16, the voids are partially air filled indicating the Rhoades et al. three-phase models suitability to unsaturated soils also.

Rhoades et al. (1989) describes the three phase model mathematically in the form of equation (4.10):

$$\sigma_a = \left[\frac{(\theta_{ss}+\theta_{ws})^2\sigma_{ws}\sigma_s}{\theta_{ss}\sigma_{ws}+\theta_{ws}\sigma_s}\right] + \theta_{sc}\sigma_s + \theta_{wc}\sigma_{wc}, \quad (4.10)$$

where θ_{ss} is the volumetric content of the solid matrix coupled in series with the pore water, θ_{ws} is the volumetric content of the pore water coupled in series with the solid matrix, σ_{ws} is the electrical conductivity of the pore water coupled in series with the solid matrix, σ_s is the electrical conductivity of the solid matrix, θ_{sc} is the volumetric content of the continuous path of the solid matrix, θ_{wc} is the volumetric content of the free pore water, and σ_{wc} is the electrical conductivity of the free pore water.

Based on the data of the study and the results of Sauer et al. (1955), Rhoades et al. (1989) forms equation (4.11) by dropping off the term $\theta_{sc}\sigma_s$ as there is no evidence of a significant conductivity through the continuous solid pathway. Lack of the conductance is assumed to be a result of too few particle to particle contacts in the solid matrix. Even more simplified equation (4.12) is introduced for situations where the pore water conductivity is rather high (over 200–400 mS/m). In the both equations θ_{wc} is substituted with θ_w - θ_{ws}, which is the difference of the total volumetric water content and the volumetric content of the coupled pore water.

$$\sigma_a = \left[\frac{(\theta_{ss}+\theta_{ws})^2\sigma_{ws}\sigma_s}{\theta_{ss}\sigma_{ws}+\theta_{ws}\sigma_s}\right] + (\theta_w - \theta_{ws})\sigma_{wc}, \quad (4.11)$$

$$\sigma_a = \left[\frac{(\theta_{ss}+\theta_{ws})^2}{\theta_{ss}}\sigma_s\right] + (\theta_w - \theta_{ws})\sigma_{wc}. \quad (4.12)$$

As a conclusion of different models describing soil electrical conductivity it can be said that rather simple models can describe electrical conductivity of coarse grained soils with high (> 400 mS/m) pore water conductivity. Complexity increases if amount of negatively charged clay particles increases. Also decreasing pore water conductivity adds complexity. For these more complex situations the two- or three-phase conductivity models can be used. In addition, no models are developed specific for soft, highly compressible and high water content clays found in Finland. The models described above have not been validated for these soils either.

5.3 Soil conductivity measurements

Measuring electrical conductivity of soil is based on feeding current to the soil and measuring potential difference between two points in the soil. As the current is known and the potential difference is measured, conductance can be determined based on the Ohms law.

From the conductance it is possible to determine conductivity of the measured soil if geometry of the current flow is known. The flow geometry determination is rather simple task for wires, but little bit more complex in a case of soil.

Here, the description of the electrical behavior of soil is made through resistivity, which unit is Ωm (ohm meters). However as discussed before, conductivity is the inverse of the resistivity so the descriptions showed next are valid for both.

Potential of a point-form current electrode in a homogeneous half space is illustrated in Figure 17. It can also be described by equation (4.13):

$$V = \rho \frac{I}{2\pi r}, \tag{4.13}$$

where V is potential, ρ is resistivity of the half space, I is feeding current, and r is distance from the electrode.

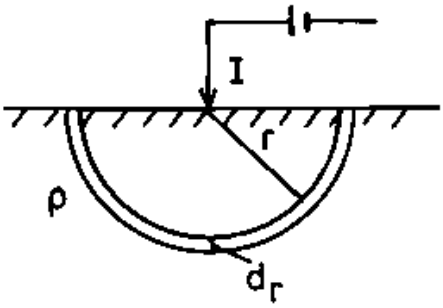

Figure 17. *Potential of a point-form current electrode in a homogeneous half space (Peltoniemi 1988, p. 131).*

The electric current flows usually through a circuit where the homogeneous half space forms a closing load. In that case, using notations of Figure 18, equation (4.14) can describe the potential of two current electrodes (A and B) in a point (M):

$$V = \rho \frac{I}{2\pi}\left(\frac{1}{r_{AM}} - \frac{1}{r_{BM}}\right). \tag{4.14}$$

However, the potential measurement is usually done by measuring potential difference of two points. In that case, the potential difference can be defined by equation (4.15):

$$\Delta V = \rho \frac{I}{2\pi}\left[\left(\frac{1}{r_{AM}} - \frac{1}{r_{BM}}\right) - \left(\frac{1}{r_{AN}} - \frac{1}{r_{BN}}\right)\right], \tag{4.15}$$

where the notation follows Figure 18.

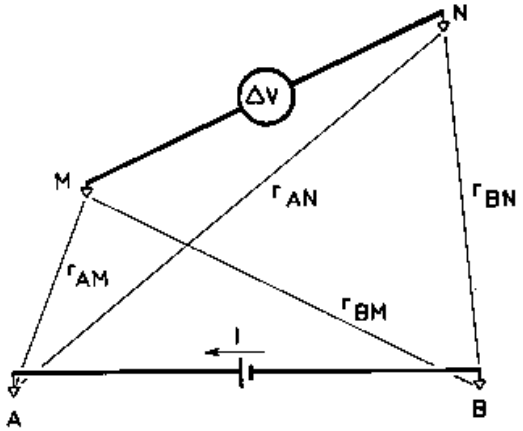

Figure 18. *Basis of general four electrode method (Peltoniemi 1988, p. 144).*

To determine resistivity of the homogeneous half space, equation (4.15) can be arranged differently to the form of equation (4.16):

$$\rho = \frac{\Delta V}{I} K, \tag{4.16}$$

where K can be defined by equation (4.17):

$$K = 2\pi / \left(\frac{1}{r_{AM}} - \frac{1}{r_{AN}} - \frac{1}{r_{BM}} + \frac{1}{r_{BN}} \right). \tag{4.17}$$

Coefficient K is purely geometrical, which's value depends only on the electrode arrangement. It can be determined for every measurement, but usually some of established electrode arrays are used. Figure 19 illustrates the different electrode arrays used usually in electrical resistivity measurements. (Peltoniemi 1988, p. 128-146)

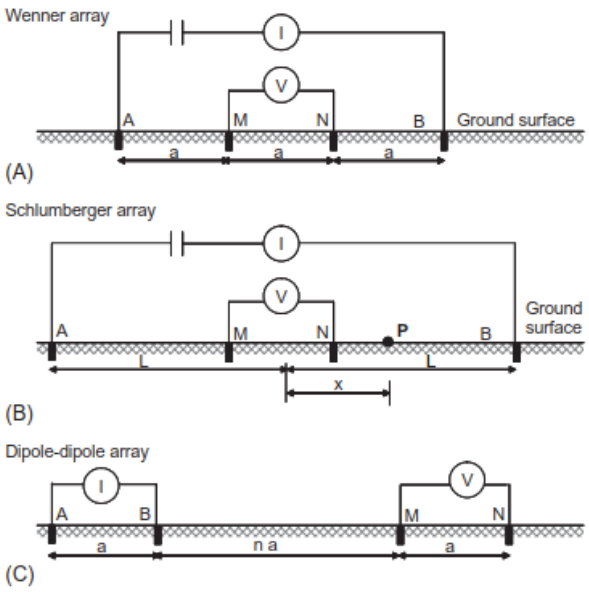

Figure 19. *Electrode arrays used in ERT measurements (Mohamed & Paleologos 2017, p. 504)*

Electrical resistivity or conductivity of soil is usually measured in two different ways. More used method is electrical resistivity tomography (ERT) where subsoil resistivity is measured from the ground surface using the electrode arrays described above. The electrodes are lined up at regular intervals. The measurement is done using different electrodes and different distances between them. Same electrode can be used for current feed and potential measurement. Depth effect of the measurement can be controlled by altering distance between the electrodes. That way, a 2D image of the resistivity of soil below the electrode line can be formed. In an ideal case, when the subsoil is homogeneous, the result of the measurement is the correct resistivity of soil. However when the soil stratigraphy is altering, the resistivity of the measurement is apparent soil resistivity complexly affected by the different layers below the electrodes. Several methods have been developed to determine the true soil resistivity from apparent values. Some of these methods assume horizontal soil layers which is not always the truth. In these cases results can be erroneous. (Peltoniemi 1988, p. 143-156)

Other method to determine soil resistivity or conductivity is the probe method. There the array (usually Wenner) is placed to a probe and the measurement is done with a single array arrangement. Then the probe is penetrated into subsoil and measurements of apparent conductivity are done with specific depths. Image from the probe method is in 1D but not so much effort is needed for building up the image. The *a* measure of the Wenner-array in probe is usually some centimeters. Due to that, the apparent soil conductivity can be assumed to describe well the true soil conductivity. However, very thin layers can effect on the measured values. In this thesis the probe method is used and the measurement is done along with a CPTU sounding with the conductivity probe module placed behind the cone. (Rhoades et al. 1999, p. 33-37)

5.4 Environmental and measurement properties affecting on conductivity

Measuring environment and technique can have significant effects on the measured conductivity of soil. Since, at least in coarse grained soils with inert solid matrix, the conduction phenomena is for the most part ionic, mobility of the ions effects on the conductivity of soil. The mobility of the ions increase with decreasing water viscosity causing conductivity to be dependent on temperature.

Temperature is usually taken into account by correcting the measured conductivity value to some reference temperature, usually to 25 °C. Correction is made with the correction factor f_T using the equation (4.18):

$$\sigma_{25} = f_T \sigma_T, \tag{4.18}$$

where σ_{25} is soil conductivity in 25 °C, σ_T is conductivity measured in temperature T and f_T is correction factor in temperature T. (Ma et al. 2011)

Ma et al. (2011) presented several temperature correction factors based on previous studies. Their recommendation for the temperature correction factor between temperatures 3–47 °C is defined by the exponential function (4.19). It is first described by Sheets & Hendrickx (1995) but equation (4.19) includes also correction presented by Corwin & Lesch (2005).

$$f_T = 0.4470 + 1.4034e^{-T/26.815}. \tag{4.19}$$

Other widely used rule of thumb correction factor described by Ma et al. (2011) is 2 %/°C.

The main measuring technique related effect on conductivity is the used measurement frequency. According to Rinaldi & Cuestas (2002) electrical conductivity of clayey soils against increasing alternating current (AC) frequency can be divided into three parts illustrated in Figure 20.

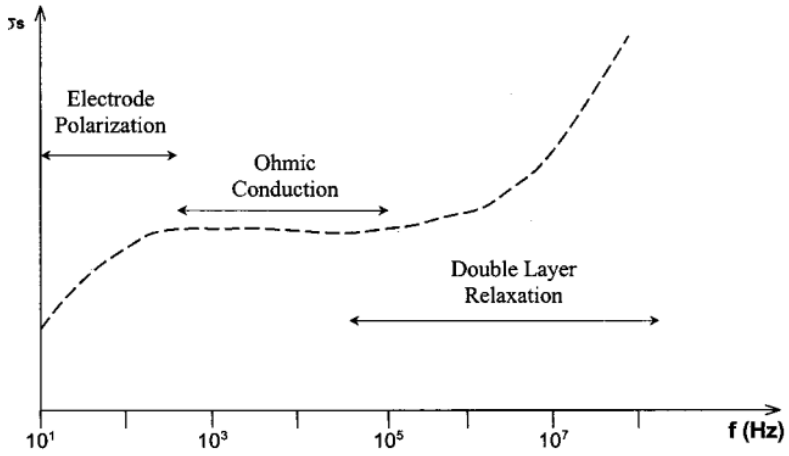

Figure 20. *Typical electrical conductivity response of clayey soil against the increasing AC measurement frequency (Rinaldi & Cuestas 2002, p. 826).*

When a direct current (DC) is applied to soil, or any ionic conductor, the current transporting ions start to move to the electrodes (anions to the positive electrode and vice versa). When the movement continues, the ions gather around the electrodes causing similar DDL effects around the electrodes as around colloidal clay particles. This thin film of ions decreases conductivity of the measurement circuit with time. The accumulation of ions of same charge causes also electrochemical diffusion forces to the system, effecting on the measurements. (Rinaldi & Cuestas 2002)

As the DC is changed to AC and frequency is increased, the ions does not have enough time to gather around the electrodes. This decreases effect of the electrode polarization as can be seen from Figure 20. When the AC frequency is increased above a certain level (around 2–3 kHz), effect of the electrode polarization diminishes. Between 3 and 100 kHz, the conductivity of soil is almost frequency independent and can be defined as ohmic. However, Friedman (2005) states soil conductivity being ohmic already above 100 Hz frequencies. (Rinaldi & Cuestas 2002)

When applying current to soil, ions in the DDL starts to slide past each other. Most of the sliding occurs in a so-called shear plane close the inner part of the DDL. In low (under 100 kHz) frequencies, the DDL ions move along the electrical field. After increasing the AC frequency above that level, the ions cannot follow the changes of the field and a phenomenon called DDL relaxation occurs increasing electrical conductivity of soil. Further increase of the AC frequency causes an increase in the conductivity making it dependent

on the frequency. This phenomenon can be used in other electrical measuring methods not discussed in this thesis. (Rinaldi & Cuestas 2002)

Rinaldi & Cuestas (2002) studied frequency dependency of electrical conductivity of pore water and soil. Some of their results are illustrated in Figures 21 and 22.

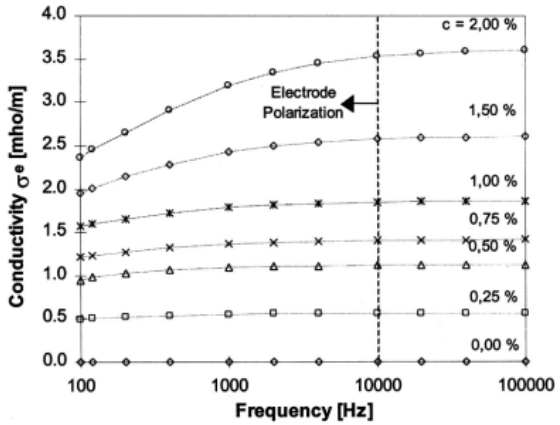

Figure 21. *Frequency dependency of electrical conductivity of NaCl electrolyte (pore water) in different concentrations (Rinaldi & Cuestas 2002, p. 827)*

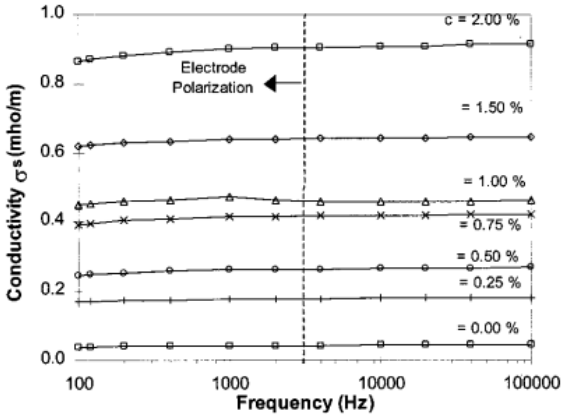

Figure 22. *Frequency dependency of electrical conductivity of constructed soil samples with different pore water salinities (Rinaldi & Cuestas 2002, p. 828)*

As it can be seen from Figure 21, conductivity of the electrolyte solution shows a clear curvilinear dependency on the frequency below 10 kHz. The curvature increases with the increasing electrolyte concentration. On the other hand, soil conductivity does not show as clear dependency on the frequency shown in Figure 22. This supports the statement of Friedman (2005) that the frequency dependency of soil conductivity becomes evident only in the very low (under 100 Hz) frequencies.

5.5 Soil properties affecting on electrical conductivity

If environment and measurement technique remains constant, electrical conductivity of soil depends on itself. The electrical conductivity of soil can be stated to be dependent on materials it is made of, proportions and structure of those. In other words, the affecting properties are mineralogy, pore water composition, porosity, volumetric water content and structure of the soil. As discussed previously, major effectors of electrical conductivity of soils are pore water conductivity and porosity (Archie 1942). When soil becomes un-saturated, volumetric water content rises more determining over the porosity.

Based on chapter 2 it could be stated that when clay content of soil increases, also mineralogy becomes a more determining factor of soil electrical conductivity. This assumption can be made since different clay minerals interact differently with pore water and its ions.

Different ions dissolved into pore water have different mobility's and interaction with clay particles. This causes dissimilarities in conductions of pore water with same concentration and different ionic compositions. Besides, Rinaldi & Cuestas (2002) found that with similar pore water conductivities but different ionic compositions also soil conductivities differ from each other. This effect is illustrated in Figure 23.

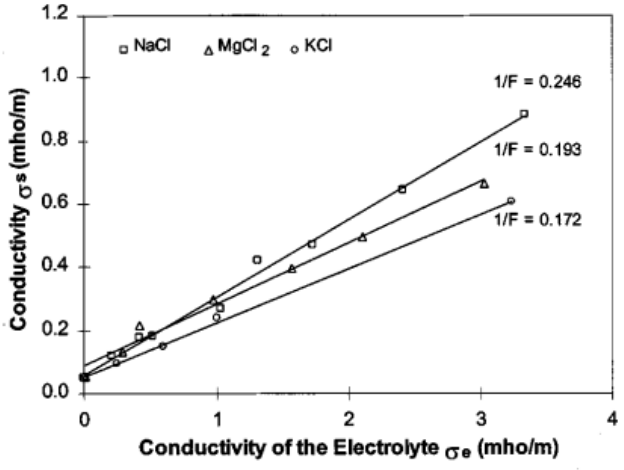

Figure 23. *Effect of pore water ionic composition on electrical conductivity of soil (Rinaldi & Cuestas 2002, p. 829).*

Structure of soil has also significant effect on electrical conductivity. Archie (1942) already found that the relation between soil conductivity and its pore waters conductivity changes along different formations. Archie (1942) found the cementation index *m* to increase with cementation giving assumption of the structure effects. Structure of soil can be defined in several levels. For example, in level of grain size distribution, arrangement and surface topology of particles. At least effect of arrangement of particles on conductivity of soil is studied. Wildenschild et al. (2000) studied the effect of clay content and

its arrangement to conductivity of sand-clay mixture samples. They found electrical conductivity of the samples to be less sensitive for changes in the pore water conductivity with high clay content and even distribution of it. Uneven distribution of the clay made the samples behave more like a clean sand sample, and changes in the pore water conductivity effected clearly to the soil conductivity. Figure 24 illustrates results of Wildenschild et al. (2000). Percentage number in the legend implies weight portion of clay mixed in sand. Word after the percentage number tells about the distribution of the clay. Dispersed mean evenly distributed clay, clusters means under 1 cm clusters mixed in the sand and parallel means parallel clay layers compacted between the sand layers.

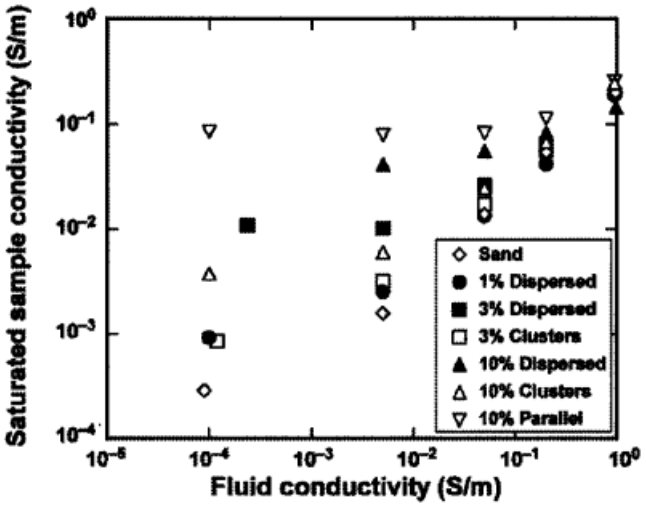

Figure 24. *Electrical conductivity against pore water conductivity of sand samples containing different amounts of clay (Wildenschild et al. 2000, p. 3086).*

Fukue et al. (1999) measured electrical properties of artificial and natural clay samples using an oedometer type device with electrodes attached to it. They measured resistivity of natural clay in undisturbed and disturbed stages in different loading conditions. They found that structure of the clay has significant effect on the resistivity. Figure 25 illustrates the resistivity measurements of Fukue et al. (1999). After 20 kPa stress level the resistivity of the undisturbed sample decreases significantly and after 50 kPa the resistivity of the undisturbed and disturbed samples are similar. Fukue et al. (1999) linked this phenomenon to bonds between clay particles and breaking of them.

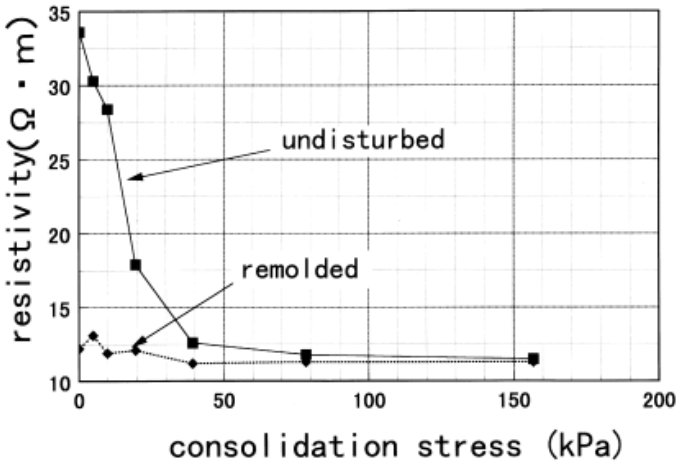

Figure 25. *Resitivity of undisturbed and disturbed natural clay samples in different stress states (Fukue et al. 1999).*

On the other hand, Nadler (1991) made parallel electrical conductivity measurements for undisturbed and disturbed samples with different pore water salinities. He found that effect of soil structure on the electrical conductivity is small and random regardless of the pore water salinity.

Effect of clay content on conductivity of sand-clay mixtures can be also seen from Figure 24. Increasing clay content increases the electrical conductivity of the samples greatly at low pore water conductivities (Wildenschild et al. 2000). When the pore water conductivity increases, effect of the clay content diminishes (Wildenschild et al. 2000).

Shevnin et al. (2007) proposed a method for determining clay content of sand clay mixtures based on resistivity measurements. They used models illustrated in Figure 26 where porosity of the soil decreases when clay is added to the sand until the clay content reaches initial porosity of the sand. From that point on, the porosity depends on the clay micro porosity and increases with further clay addition.

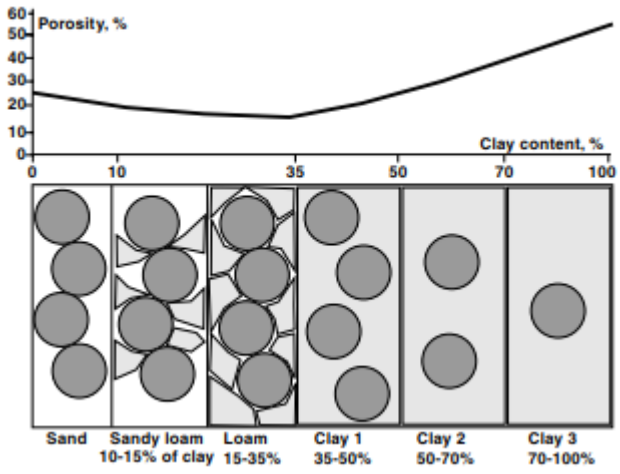

Figure 26. *Clay content dependency of porosity for sand-clay mixtures (Shevnin et al. 2007, p. 266)*

The main assumption in Shevnin et al. (2007) model is that when clay content of sand-clay mixture is below initial sand porosity, electrical conductivity of the mixture depends on combined conductivity of the free pore water in sand pores and conductivity of the pore water in the clay micro pores. From full clay saturation point on, the conductivity is only depending on the clay micro pore conductivity. The theoretical prediction of Shevnin et al.'s (2007) model and some experimental results are illustrated in Figure 27.

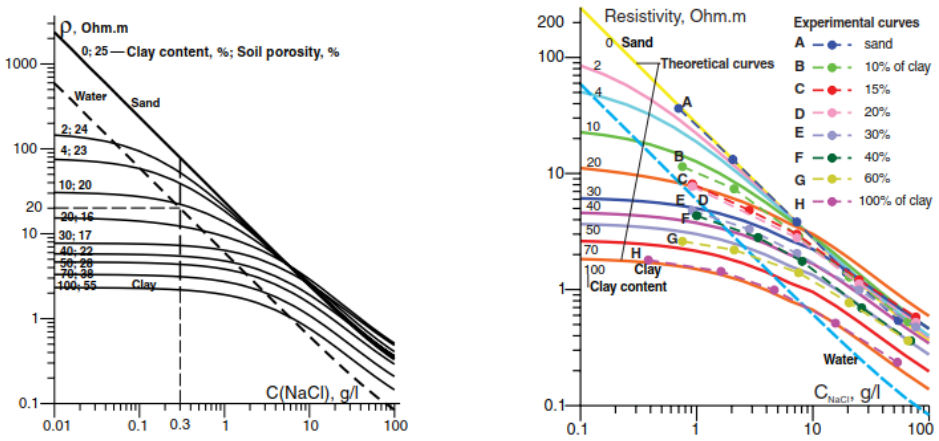

Figure 27. *Theoretical model and measurement results of relation between apparent resistivity and clay content (Shevnin et al. 2007).*

Figure 27 shows that with similar pore water conductivities, increasing clay content increases electrical conductivity of soil. The change is much higher with low pore water salinities and diminishes with increasing salinity.

As a conclusion of the factors effecting on electrical conductivity of soil, it can be said that pore water conductivity plays key role in almost every correlation. It seems to intensify effects of some properties, for example effect of clay content, while it is low. On the other hand, other effects are in most cases diminished when the pore water conductivity increases to sufficiently high values. Also clay content seems to make conductivity phenomenon more complex at least when comparing results with zero and few percent clay content.

6. TESTING PROCEDURE AND SITES

This thesis is done as a part of the Fincone project that includes site investigations on several different sites across Finland. Seven of the Fincone sites are chosen to this thesis. Pore water salinity was determined from all of those except for the Masku site.

Field tests included CPTU soundings and field vane tests (FVT) performed with TUTs drill rig and sampling done by a sub-consultant. The sampling was mainly done using TUTs Laval type open drive tube sampler (sample diameter 132 mm) (Di Buò et al.) and ST1 type piston sampler (sample diameter 50 mm). In Perniö site, also mini block sampler (sample diameter 150 mm) (Long et al. 2016) was used. In determination of index parameters no difference between the samplers were done. Di Buo (2017) and Long et al. (2016) define sampling procedure of the TUTs tube sampler and mini block sampler respectively.

6.1 Field tests

CPTU soundings and FVTs were done using TUTs drill rig seen in Figure 28. The rig contains A. P. van den Bergs CPTU and FVT systems. CPTU system composes of Icontrol data logger and digital penetration cone called Icone. The system provides possibility to attach either conductivity or seismic module behind the CPTU cone. In this thesis, electrical conductivity of soil is measured using this conductivity module. FVT apparatus includes down hole vane, where torque apply and measurement is done down hole about half a meter above the vane. Further description of the FVT apparatus is given by Selänpää et al. (2017). CPTU and FVT were done according to guidelines followed in Finland (Kairausopas 2 : Siipikairaus 1995; SFS-EN ISO 22476-1 2013; Geotekniset tutkimukset ja mittaukset : Suunnitteluvaiheen ohjaus 2015)

Figure 28. *TUTs drill rig (Di Buo 2015)*

Conductivity module of the A. P. van den Bergs CPTU apparatus is shown in Figure 29, and its electrode setup and dimensions in Figure 30. The module uses a Wenner array to determine electrical conductivity of surrounding soil. Measuring range of the module is 50 – 1500 mS/m, and its inaccuracy is 5 % of the reading and at least 1 mS/m. The measurement is done by applying continuously altering known current between the outer electrodes so that potential difference between the inner electrodes stays at a constant level of 50 mV. Polarization effects and electrode contamination is avoided by using an AC at frequency of 650 Hz. (Länsivaara et al. 2016)

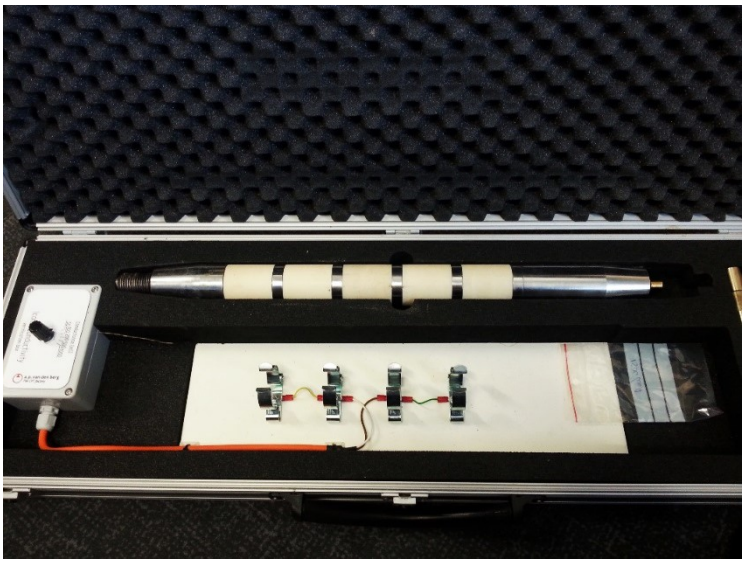

Figure 29. *Conductivity module (Selänpää 2014).*

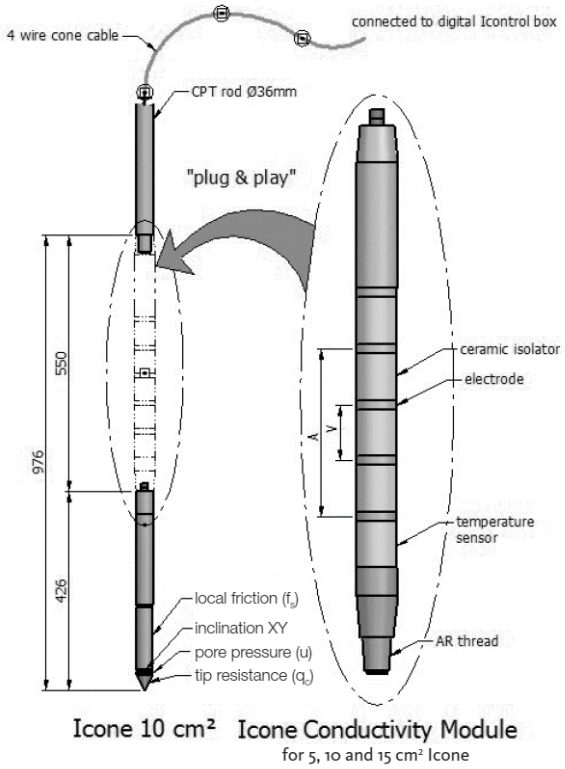

Figure 30. *Electrode arrangement and measurements of the Icone conductivity module* (Icone Conductivity Module, easy acces to additional data with a click-on module 2015)

Measurements were done according to manufacturer's guidelines but data handling was developed in the Fincone project. Raw data of the conductivity measurements is not used in correlations, but an average is taken from all the conductivity measurements of same site. Every site contains 1–3 CPTU soundings with the conductivity module. The average data is also filtered using sliding average of 8 cm to prevent unwanted deviation seen in it. This enables to see interesting changes in conductivity, and sharp peaks in the data does not effect on correlations. CPTU cone included temperature probe also, so the soil temperature was known. This data was used to correct soil conductivity to reference temperature 25 °C.

Penetration speed of the standard CPTU sounding is 20 mm/s and data is gathered every 20 mm. Same penetration speed and data acquisition frequency is also used with the conductivity module. However, depth of the measurement is logged from the tip of the cone so the data must be depth corrected before correlating it to other data. The depth correction is done to the middle point of the module so that real depth of the measured value is measured depth minus 70 cm.

Sampling was done by VR-Track Oy, which worked as a sub-consultant. Sampling was done based on CPTU data, where homogenous layers were tried to find to provide as homogenous samples as possible for purposes of the project. Due to that, samples are not taken through the whole layer and there might be some lack of data in certain depths of some of the sites.

6.2 Laboratory tests

Total set of Fincone project laboratory tests included large number of different index testing and numerous triaxial, direct simple shear (DSS) and oedometer tests to define strength and deformation properties. All test were done in geotechnical laboratory of TUT. The index tests were done according to standards specified in Table 3.

Table 3. *Index parameters measured in laboratory and standards along those were measured.*

Measured parameter	**Standard**
Water content	SFS-EN ISO 17892-1
Plastic limit	CEN ISO/TS 17892-12:fi (adapted)
Liquid limit (fall cone)	CEN ISO/TS 17892-12:fi
Particle size distribution	PANK-2103
Organic content	GLO-85
Intact strength (fall cone)	SFS-EN ISO 17892-6:2017
Remolded strength (fall cone)	SFS-EN ISO 17892-6:2017
Pore water electrical conductivity	-

Water content (w) was determined using oven drying in 110 °C. Maximum grain size of samples were in most cases under 2 mm, so wet mass of the samples used in determinations were around 100 g. The samples were weighted before and after oven drying and the water content was determined based on those. (SFS-EN ISO 17892-1:en 2015)

Plastic limit (PL) was determined by imitating technical specification CEN ISO/TS 17892-12:fi (2008). Difference between used method and the technical specification was that with the used method three divided samples of same main sample was used for determination when the technical specification requires two parallel samples divided in four to determination. Divided sample was rolled against table to 3 mm thick strip and gathered back to a ball until the sample was dried so much it started to crack when rolled. When the cracking started, the rolling was stopped and water content was determined by oven drying. Same procedure was done for the other divided samples and plastic limit was determined by an average of the measured water contents.

Liquid limit (LL) of the samples were determined using fall cone apparatus according to technical specification (CEN ISO/TS 17892-12:fi 2008). Liquid limit was determined by one point method where the liquid limit is determined simultaneously with remolded strength. Plasticity index (PI) was determined as a difference between PL and LL.

Classification of soil plasticity was made according to guideline (Korhonen et al. 1974). In that, soil is determined as highly plastic when *PI* is over 25, moderate plastic when *PI* is 10–25 and low plastic as *PI* is under 10.

Particle size distribution was determined by sedimentation using hydrometer according to guideline (PANK-2103 2002). A dried sample was grounded and sieved through 2 mm sieve. After that 50 grams of sieved sample was weighted to measuring glass (1000 ml) and stirred with about 300 ml of distilled water and 50 ml of dilute sodium-pyro-phosphate solution. After the stirring, the solution was leaved to stand at least overnight. On the next day, the solution was extended to 1000 ml by adding distilled water and formed solution was stirred again. After the new stirring the measuring glass was turned back and forth 10 times and then the glass was placed back on the table. Then the actual measuring started. Specific density of the solution was measured using hydrometer, and the grain size distribution was defined based on that. Measurements were done 1 min, 6 min, 1 h, 5 h, 24 h and 4 days after starting of the test. Also temperature of the solution was measured after specific density measurement to correct the passing percentage. The passing percentages were calculated using ready-made excel form used in the laboratory.

Activity of soil was determined as a ratio of *PI* and clay content (Skempton 1953). Activity indicates mineral structure of clayey soil. In addition, it illustrates the total particle-pore water composition since salinity of the pore water effects on plastic properties of the soil. (Mitchell 1976, p. 179-181) Soil activity is classified based on Skempton's (1953) publication. In that, clays with activity over 1.25 are named active, clays with activity between 0.75–1.25 are called normal, and clays with activity under 0.75 were described inactive.

Liquidity index (*LI*) was determined from *PI* and *w* results with the equation $LI = (W-PL)/PI$. *LI* illustrates consistency of soil. (Mitchell 1976, p. 222-226)

Organic contents of the samples were determined using burning method as on average of two parallel samples. A dry soil sample was first sieved through 2 mm sieve and then dried again. After the drying, 10–50 grams of the sample was measured to weighted crucible and then total weight of the crucible and sample was weighted. After weighting, the samples were burned in 800 °C for 1 hour and cooled. The cooled samples were weighted again and the organic content was determined by a loss of ignition. Effect of evaporated crystal water was estimated using correction coefficient illustrated in Figure 31. (Suomen geoteknillinen yhdistys 1985)

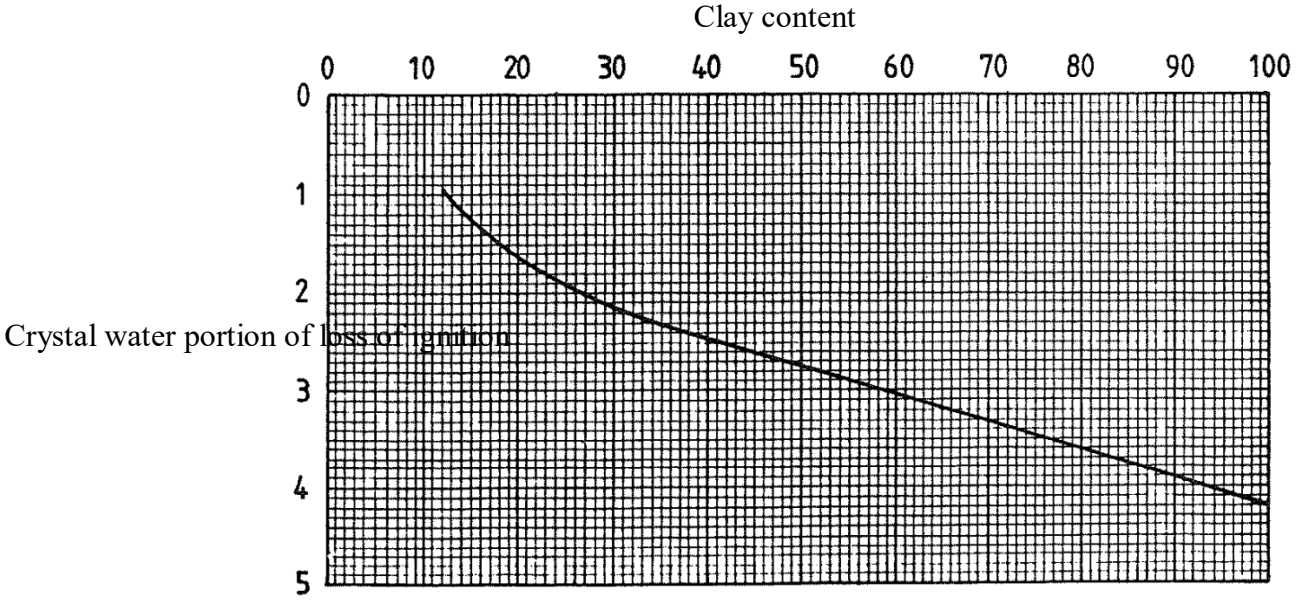

Figure 31. *Crystal water correction in organic content determination (Suomen geoteknillinen yhdistys 1985).*

Intact undrained shear strength (s_u) of the samples was determined using fall cone test. Appropriate cone was selected so that settlement of the cone was 4–11 mm. At least 5 drops were done. The settlement, defining undrained shear strength, was calculated as an average of three intermediate settlements of five drop series. (SFS-EN ISO 17892-6:2017:en 2017)

Remolded undrained shear strength (s_{ur}) was determined also by using fall cone test. Sample was remolded vigorously either in a cup with spatula or in resealable plastic bag. Then the sample was inserted to a drop cup and levelled along the upper edge of the cup. Then the dropping of the cone was done and the settlement was measured. Dropping was repeated at least five times so that settlement was not clearly growing. Between every drop, the sample was remolded again and levelled. The settlement, defining the undrained shear strength, was taken as an average of series of five last drops where largest and smallest settlement were not taken into account. Sensitivity (S_t) of the samples was determined as a ratio of remolded and intact strengths. (SFS-EN ISO 17892-6:2017:en 2017) Clays were classified by sensitivity using guideline (Korhonen et al. 1974). In that, soil is defined as

highly sensitive when S_t exceeds 30, as moderate sensitive with S_t between 10–30, and low sensitive with S_t under 10.

Pore water conductivity measurement was done using Consort conductivity meter. Firstly, pore water sample was extruded from the sample using device seen in Figure 32. The sample was firstly thoroughly remolded and then inserted into the extruder cell on top of a filter paper. The soil was preciously sealed on the walls of the cell to prevent air pressure escaping from the bottom part of the cell. Then the top part of the cell was placed on its place and the cell was closed and tightened. Then air pressure of about 10 kPa was applied on the top part of the cell to ensure sealing of the cell. After the ensuring, the air pressure was increased with rate of about 10 kPa in every 15 minutes to the final pressure between 40–60 kPa. Extruded pore water was gathered to a small measuring glass with volume of about 100 ml. When enough of pore water was extruded, the pressure in the cell was released and pore water sample was moved to conductivity meter. The conductivity of the pore water was measured in the measuring glass using probe seen in Figure 32. Before every measurement, the conductivity meter was calibrated using potassium chloride (KCl) solution in concentration of 0.1 mol/l. Before measurement of the actual pore water sample, the probe was rinsed with distilled water and dried to prevent contamination of the sample. After conductivity measurement, temperature of the pore water sample was measured using spirit thermometer. The value, given by the meter, was a temperature corrected one. Correction was done to reference temperature of 25 °C. Correction factor, used by the meter, was not determined.

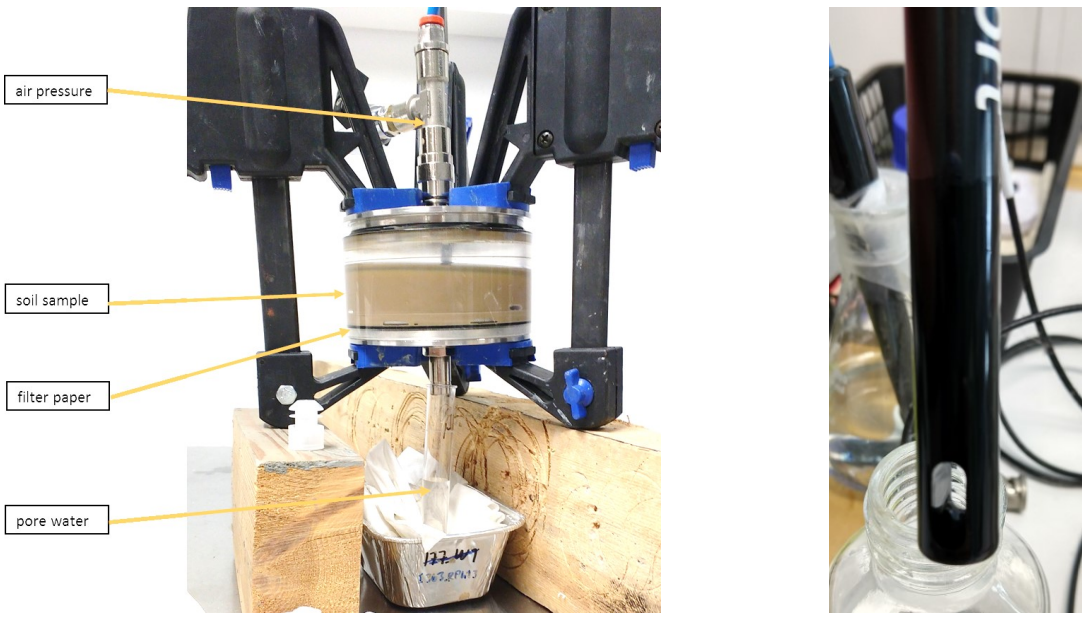

Figure 32. *Pore water extruder (left) and conductivity probe (right).*

Salinity of pore water was determined from its conductivity using the equations (6.1)–(6.5). Firstly, practical salinity (S) can be defined using the equation (6.1):

$$S = a_0 + a_1 R_t^{1/2} + a_2 R_t + a_3 R_t^{3/2} + a_4 R_t^2 + a_5 R_t^{5/2} + \Delta S, \quad (6.1)$$

where R_t is conductivity ratio described later, a_i's are coefficients. ΔS denotes for:

$$\Delta S = \frac{(t-15)}{1+k(t-15)}\left(b_0 + b_1 R_t^{1/2} + b_2 R_t + b_3 R_t^{3/2} + b_4 R_t^2 + b_5 R_t^{5/2}\right), \quad (6.2)$$

where t is temperature (°C) and k and b_i's are coefficients. The conductivity ratio R_t is given by the equation (6.3):

$$R_t = \sigma(S,t,0)/\sigma(35,t,0), \quad (6.3)$$

where $\sigma(S,t,0)$ refers to conductivity of water sample in salinity S, temperature t (°C) and in atmospheric pressure (0) and $\sigma(35,t,0)$ is electrical conductivity of the (reference) solution with salinity $S = 35$ in temperature t (°C) and atmospheric pressure. (Fofonoff & Millard 1983, p. 6-8)

Conductivity $\sigma(35,t,0)$ can be defined by the equation (6.4)

$$r_t = \sigma(35,t,0)/\sigma(35,15,0), \quad (6.4)$$

where $\sigma(35,15,0)$ is electrical conductivity of the reference solution with salinity of 35 in the reference environment (t = 15 °C, atmospheric pressure). Conductivity of the reference solution in the reference environment used in calculations of this thesis is 42.91599 mS/cm (Culkin & Smith 1980). The ratio r_t,in the equation (6.4), is defined by the equation (6.5):

$$r_t = c_0 + c_1 t + c_2 t^2 + c_3 t^3 + c_4 t^4, \quad (6.5)$$

where t is temperature (°C) of the sample during conductivity measurement and c_i's are coefficients. The coefficients used in the equations (6.1)–(6.5) are:

$a_0 = 0.0080$	$b_0 = 0.0005$	$c_0 = 0.6766097$
$a_1 = -0.1692$	$b_1 = -0.0056$	$c_1 = 0.0200564$
$a_2 = 25.3851$	$b_2 = -0.0066$	$c_2 = 1.104259*10^{-4}$
$a_3 = 14.0941$	$b_3 = -0.0375$	$c_3 = -6.9698 *10^{-7}$
$a_4 = -7.0261$	$b_4 = 0.0636$	$c_4 = 1.0031*10^{-9}$
$a_5 = 2.7081$	$b_5 = -0.0144$	
$\sum a_i = 35.000$	$\sum b_i = 0.000$	$k = 0.0162.$

(Fofonoff & Millard 1983, p. 6-8)

Among practical salinity and temperature, conductivity measured from pore water sample is also a function of air pressure affecting at the time of the measurement. However, the change in the air pressure between the measurements is evaluated to be so small and other factors, for example sample preparation, are evaluated to have much larger effect on the measurement. Due to that, the effect of the air pressure is omitted in this thesis.

As written by Fofonoff & Millard (1983) the equation (6.1) yields values of practical salinity, which is a unitless value. Conductivity of seawater is referred to the standard solution of potassium chloride (KCl), which concentration and electrical conductivity are known. Even though the practical salinity is unitless, in this thesis its value is assumed to be ‰ or g/l where density of the pore water is assumed to be 1 g/cm^3. This is done to ease the comparison of the results to other studies. These assumption can be made, since practical salinity is concentration (g/l) of such solution where the electrolyte is solely KCl, and error caused by different electrolytes is assumed to be negligible in applications of this thesis.

6.3 Testing sites

The testing sites of this thesis were chosen from the Fincone sites. All the sites located near railway lines except for the Murro site. Pore water salinity was determined from all the other sites except for Masku. The included sites are presented in this chapter. Presentation composes of general description of the site, its topography, and soil conditions. Also generalized stratigraphy of the deposit is explained. Soil properties are shown in concluding tables for each site. Reading those tables, it must be kept in mind that for properties determined in laboratory, especially pore water conductivity and salinity, the range given might not represent the whole layer. This is due to that, samples were not taken through the whole layer but from specific homogenous layers so gaps in data might exist. On the other hand, the soil conductivity (σ) represents the whole layer.

Deposits are also tried to divide in sediment layers representing different phases of the Baltic Sea. Division is made primary based on clay, organic and water contents of the deposits. This is not though a rigorous method since, as discussed before, different sediments are not easily identified based on only geotechnical data. This concerns especially when trying to separate Ancylus and Yoldia sediments. Some of the sites have also been near ancient or present river channels which have effected on the sites adding complexity to the sediment identification.

The full soil investigation data is shown in figures with elevation in appendices. Elevation of the ground surface is measured at each site during sampling and the elevation of the properties are calculated based on that. Ground surface is showed in all figures, and sea level when it is appropriate. The sea level is assumed to be at elevation 0 m. Evaluated layers of certain Baltic Sea phase sediments are sketched to water content and conductivity plots. Laboratory forms have not been included to this thesis as appendices, since during the Fincone project a database concluding all the data measured is about to create.

6.3.1 Perniö

In 2009 FTA and TUT arranged full scale failure test of railway embankment in the Perniö site (Lehtonen 2010). Within the framework of the test, the site was intensively investigated with several in-situ and laboratory methods. After the test, the Perniö site has been in interest of lot of studies (Lehtonen 2015; Mansikkamäki 2015; Mataic 2016; Löfman 2016; D'Ignazio 2016), and data has been gathered with different methods during several years. During the Fincone project, data has been collected with three different site investigation sessions during years 2014–2016. The data used in this thesis is mainly from years 2015 and 2016.

Topography of the Perniö area is fluctuating where valleys of deep clay deposits alters with high and sharp peaks of bedrock hills (Lehtonen 2010, p. 23-30). The site lies near Helsinki–Turku railway line in deep clay deposit area. The deposit consists of a 1 m thick dry crust underlaid by about an 8 m thick clay layer followed by stiffer silty and sandy layers. Ground surface at the site lies in elevation of + 7.4 m. Site investigations are concentrated to the soft clay layer, which is named as Perniö clay.

Figure 33 illustrates topography and topsoil formations of the Perniö site and near surroundings. The topography is shown with shading and the soil formations with colors. Red color refers to bedrock denudation, light blue to clay formations, and brown to moraine formations. As it can be seen from the figure, the Perniö site lies in a possible old river valley that has been formed between bedrock hills. The present river is probably remain of the ancient river on to which bottom part of the Perniö clay is sedimented.

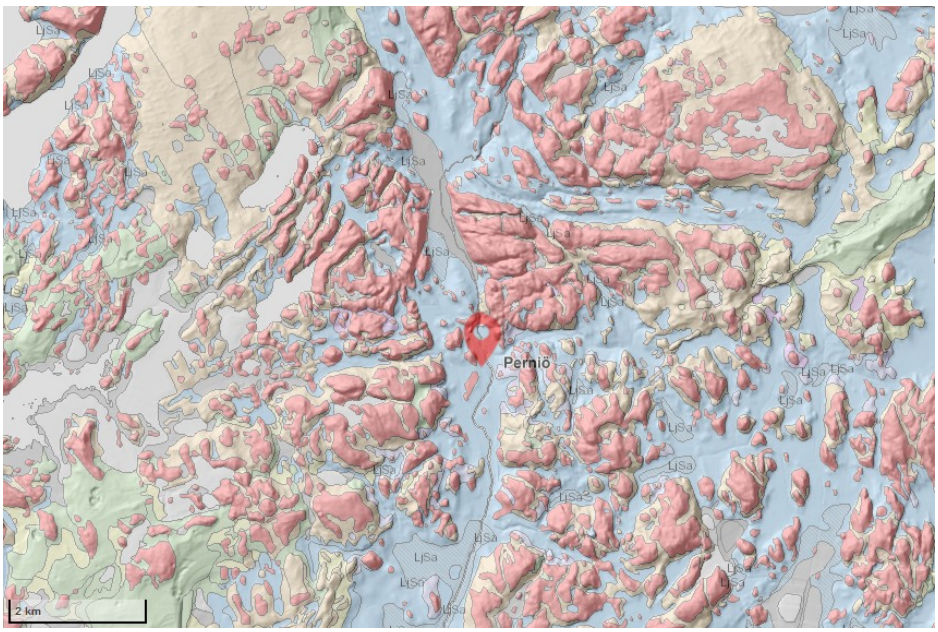

Figure 33. *Topography and topsoil formations of Perniö site (Taustakartta ; Rinnevarjostus ; Maaperä)*

Table 4 illustrates variations in the Perniö clay properties. Full report of the properties is shown in appendix A. Based on the soil investigation results the Perniö clay can be defined as highly plastic sensitive clay. There is some deviation in the results between layers presented in the next paragraph

Table 4. *Ranges of the Perniö clay properties.*

Limits of variation	w [%]	PL [%]	LL [%]	PI [%]	LI -	Clay content [%]	Organic content [%]
Upper	111	34	75	41	2.5	89	2.1
Lower	73	23	45	21	1.6	52	0.0
Limits of variation	**Activity -**	**S_u [kPa]**	**S_{ur} [kPa]**	**Sensitivity -**	**σ [mS/m]**	**σ_w [mS/m]**	**S [g/l]**
Upper	0.79	20	1.6	72	175	254	1.4
Lower	0.34	9	0.2	7	72	136	0.7

When the data from site investigations is combined with the soil map and topography of the site, the Perniö clay can be divided into sediments of different phases of the Baltic Sea. Sandy/silty formation on the bottom of the deposit might be formation of Baltic Ice Lake. On top of the coarser layer until elevation of +2 m is likely a Yoldia Sea formation. High clay and water contents support this assumption. Between elevations +2–+4 m there is probably an Ancylus Lake sediment. Lower clay content compared to the assumed Yoldia sediment and generally low organic content support this idea. On the top most under the dry crust there is probably a Litorina sediment. Relatively high organic and water contents refer to that. Fairly low salinity of the top layers pore water can be explained by the diluting effect of rain water percolation.

6.3.2 Sipoo

The Sipoo site lies in the southern part of Finland approximately 30 km to the north-east of the city of Helsinki between the communes of Kerava and Nikkilä. The site lies along railway line between Kerava and Sköldvik. Overall Topography of the Sipoo site is somewhat similar to the Perniö where large open areas of clayey soil beds alter with sharp peaks of bedrock hills. To the south from the Sipoo site, soil thickness decreases and bedrock denudations becomes more abundant. Soil profile of the site consist of about a 1 m thick dry crust layer underlaid by a transformation layer. After the transformation layer, the soil profile consists of a more or less homogeneous soft clay layer in 12.5 m thickness. The clay layer contains some coarser layers in very small thickness. A variable silty/sandy soil layer underlays the clay layer. The properties of the clay layer are determined from 7 m thick layer of soft clay between elevations +20–+13 m and this is named as Sipoo clay.

Figure 34 illustrates topography and topsoil formations of the Sipoo site. Legend is similar with the Figure 33. Sipoo site lies on the edge of a river valley near moraine-covered hill. At least in some point after the last glacier the river might have had effect on the Sipoo site sediments.

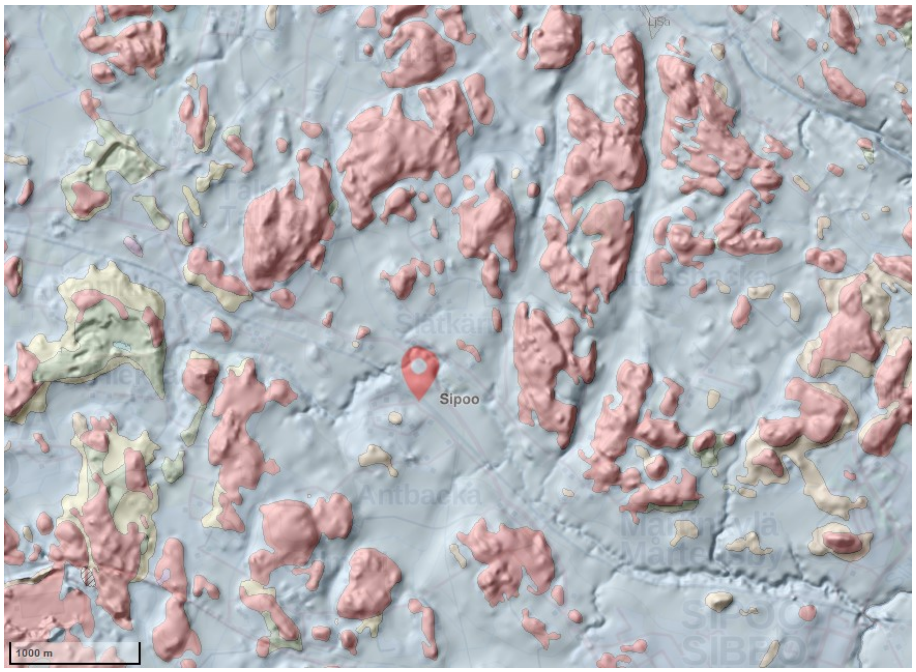

Figure 34. *Topography and topsoil formations of the Sipoo site (Taustakartta ; Rinnevarjostus ; Maaperä).*

Table 5 shows the ranges of the Sipoo clay properties and full report of the results is shown in appendix B. Overall, the Sipoo clay is highly plastic and moderate sensitive inorganic clay. The clay content is extremely high and contrary the pore water salinity is low, at least compared to the Perniö clay. The Sipoo clay consists very likely of Ancylus and Yoldia sediments.

Table 5. *Ranges of the Sipoo clay properties.*

Limits of variation	**w [%]**	**PL [%]**	**LL [%]**	**PI [%]**	**LI -**	**Clay content [%]**	**Organic content [%]**
Upper	116	32	94	63	1.8	94	1.4
Lower	86	27	61	33	1.2	64	0.0
Limits of variation	**Activity -**	**S_u [kPa]**	**S_{ur} [kPa]**	**Sensi-tivity -**	**σ [mS/m]**	**σ_w [mS/m]**	**S [g/l]**
Upper	0.72	18	1.2	45	126	79	0.4
Lower	0.50	15	0.3	16	63	40	0.2

When the soil map and soil investigation data are combined, the Sipoo clay can be divided into sediments of the different phases of the Baltic Sea. Under the dry crust there is likely an Ancylus sediment layer. This conclusion can be made based on clay content (around 60 %), low organic content and salinity of the pore water. Below that is very likely Yoldia sediment layer, since clay content is extremely high and organic content is low. Below the Yoldia sediment, there is very likely Baltic Ice Lake sediment. No samples were taken from that layer but CPTU results show existence of coarser layers.

6.3.3 Paimio

Overall topography of the Paimio site is similar with the Perniö site, since both of them locate on the south-western coast of Finland. As Perniö also the Paimio site locates next to the Helsinki–Turku railway line but about 35 km to the north-west of Perniö. Soil profile of the Paimio site consists of a 1 m thick dry crust layer underlaid by similar transformation layer as in the Sipoo site in 1 m thickness. After the transformation layer, more or less homogenous soft clay layer follows in 11 m thickness underlaid by silty/sandy layer. Determination of the soil properties is done from layer between levels of +19–+13 m named Paimio clay. Ground surface exists at level +22.3 m. Special feature of the Paimio site was an artesian ground water which started to flow from boreholes after the soundings.

Figure 35 illustrates topography and topsoil formations of the Paimio site. It lays on a channel between bedrock hills. The site itself is flat but on the edges, hills rise sharp and high. In the channel some kind of river has probably flown.

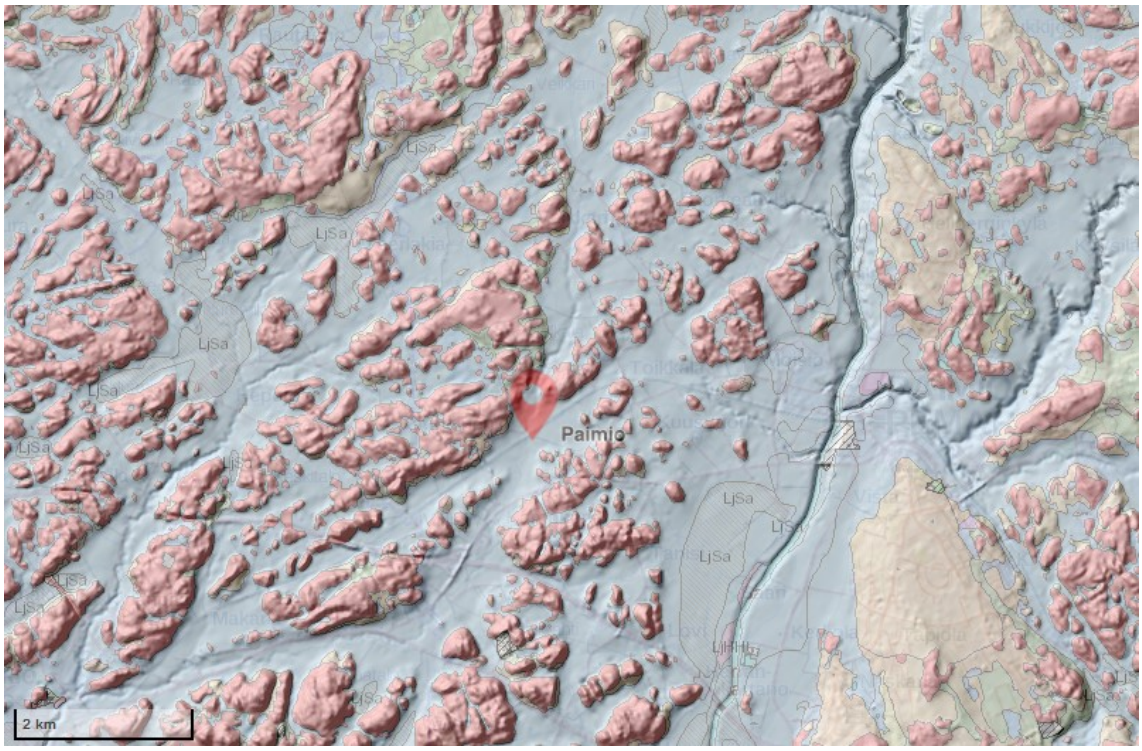

Figure 35. *Topography and topsoil formations of the Paimio site (Taustakartta ; Rinnevarjostus ; Maaperä).*

Table 6 contains ranges of the determined properties of the Paimio clay. As a conclusion Paimio clay can be defined as highly sensitive moderate plastic clay with low pore water salinity. Clay content seems to be very high and organic content so low that the Paimio clay can be defined totally as inorganic.

Table 6. *Ranges of the Paimio clay properties.*

Limits of variation	**w [%]**	**PL [%]**	**LL [%]**	**PI [%]**	**LI -**	**Clay content [%]**	**Organic content [%]**
Upper	112	31	66	36	3.0	98	0.0
Lower	46	21	39	16	2.1	41	1.1
Limits of variation	**Activity -**	**S_u [kPa]**	**S_{ur} [kPa]**	**Sensi-tivity -**	**σ [mS/m]**	**σ_w [mS/m]**	**S [g/l]**
Upper	0.44	20	1.4	99	109	61	0.3
Lower	0.24	13	0.2	52	77	50	0.3

When the soil map and soil investigation data are combined, the Paimio clay can be divided to sediment layers of different phases of the Baltic Sea. Below dry crust there is probably an Ancylus sediment layer between levels +17–+20 m. Sufficiently high clay content and low organic content refers to that. Under Ancylus layer there is likely a Yoldia sediment, since the clay content is very high and organic content remains low. Litorina sediments seems to be missing from the Paimio site.

6.3.4 Kotka 238

Kotka 238 site lies along Kouvola–Kotka railway line near Kotka operating point. Overall topography of the Kotka area is fluctuating with lots of different soil formations and bedrock denudations. The Kotka 238 site is near the Kymijoki river and the Baltic Sea coast line with elevation of only 1.6 m above current sea level. Soil profile consists of an about 1 m thick dry crust layer followed by a softer layer of about 0.5 m thick. Below that is again a 1 m thick stiff layer. About 6 m thick soft clay layer underlays those surface layers followed by altering silty/sandy soil layer. Laboratory and field tests are focused on the soft clay layer named as Kotka 238 clay.

Topography and topsoil formations of the Kotka 238 site are illustrated in Figure 36. As it can be seen from the figure, the site locates near the coastline of the Baltic Sea on the mouth of the Kymijoki River. Soil map shows blue and purple formations, which refers to clayey and silty soils. This might be due to deposition effect of the river. Red color in the figure refers to bedrock denudations and brown and yellow colors to moraine formations.

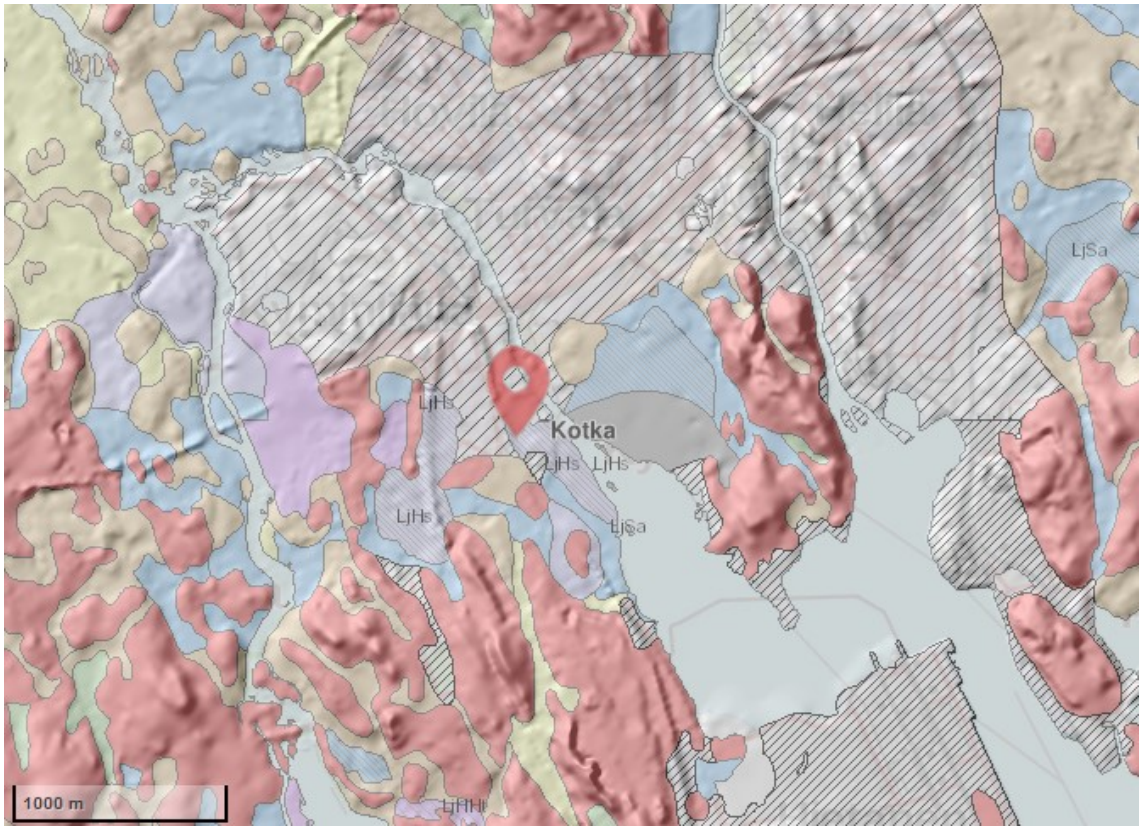

Figure 36. *Topography and topsoil formations of the Kotka 238 site (Taustakartta ; Rinnevarjostus ; Maaperä).*

Table 7 shows the ranges of the properties determined from the Kotka 238 clay. There are two distinguishing layers in the Kotka 238 clay which presented in the next paragraph. Top layer can be defined as organic moderate plastic high sensitive lean clay and lower layers as non-organic high plastic and moderate sensitive fat clay.

Table 7. *Ranges of the Kotka 238 clay properties.*

Limits of variation	**w [%]**	**PL [%]**	**LL [%]**	**PI [%]**	**LI -**	**Clay content [%]**	**Organic content [%]**
Upper	111	35	90	55	2.2	87	4.9
Lower	38	19	42	16	1.2	32	0.0
Limits of variation	**Activity -**	**S_u [kPa]**	**S_{ur} [kPa]**	**Sensi-tivity -**	**σ [mS/m]**	**σ_w [mS/m]**	**S [g/l]**
Upper	1.7	29	1.2	38	220	405	2.3
Lower	0.3	11	0.3	15	95	354	1.9

By combining data from the soil map and soil investigations, Kotka 238 clay can be divided into sediments of different phases of the Baltic Sea. Below dry crust layer there is very likely some river formations and few sampling was performed on to that. Below that between levels 0 m–-3 m, there is likely a Litorina sediment layer. This assumption is supported by high water and organic contents and moderate clay content. Under the Litorina sediment lies probably an Ancylus sediments layer. Higher clay and lower organic contents compared to the Litorina sediment indicates that. Low pore water salinity of the Litorina sediment can be explained by diluting effect of water percolation.

6.3.5 Kotka 233

Kotka 233 site lies along the same Kouvola–Kotka railway line as Kotka 238 site but about 4 km to the north of there. Around the Kotka 233 site, wide fine grained soil beds spread out. Soil profile consists of about 1 m thick dry crust layer following with a transformation layer of also about 1 m thick. Below that is about 8 m thick soft clay layer with some thin silty layers. Ground surface locates at elevation of +10 m. Laboratory and field tests are focused on the soft clay layer named as Kotka 233 clay.

In Figure 37, topography and topsoil formations of the Kotka 233 site are illustrated. It lies near the channel of the Kymijoki River but is a part of wider low laying area that spreads to the east of it.

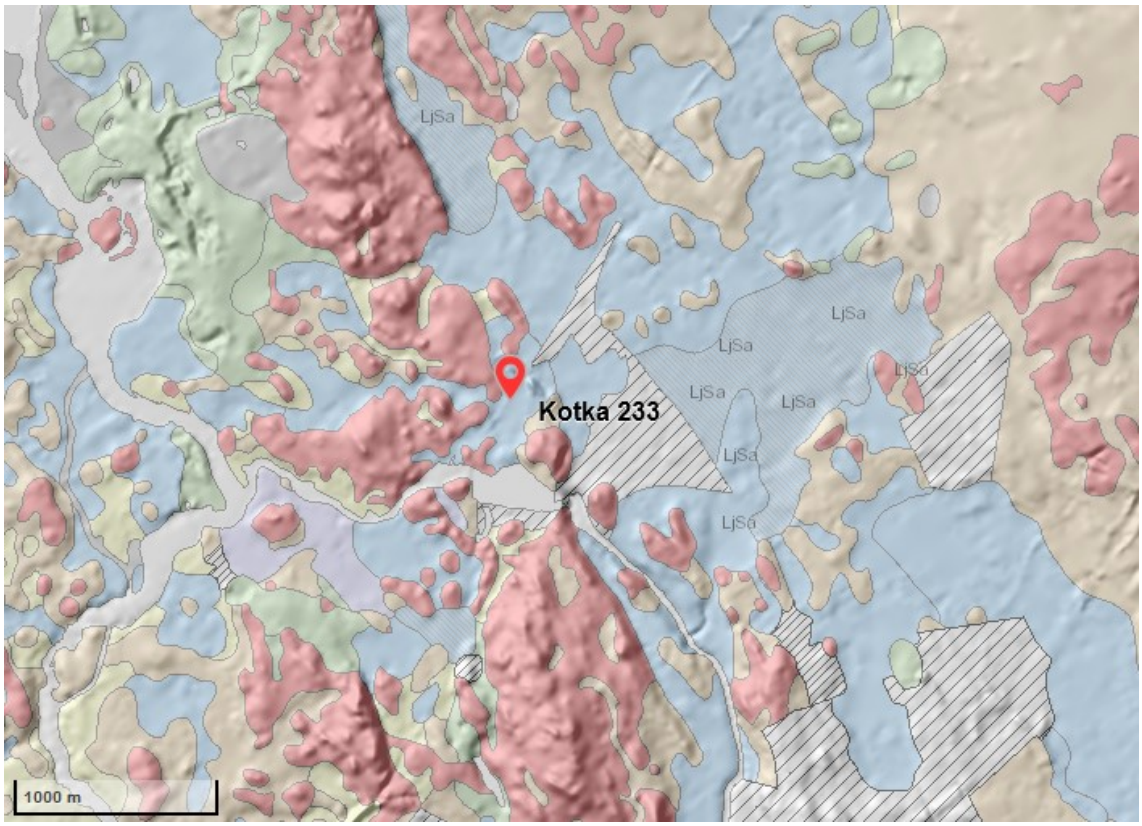

Figure 37. *Topography and topsoil formations of the Kotka 233 site (Taustakartta ; Rinnevarjostus ; Maaperä)*

Table 8 concludes the properties of the Kotka 233 clay. Two layers can be separated from the deposit. Top part of the Kotka 233 clay can be defined as organic moderate sensitive and highly plastic clay. On lower levels, the clay is highly sensitive moderate plastic and inorganic.

Table 8. *Ranges of the Kotka 233 clay properties.*

Limits of variation	**w [%]**	**PL [%]**	**LL [%]**	**PI [%]**	**LI -**	**Clay content [%]**	**Organic content [%]**
Upper	126	43	95	52	2.0	56	3.5
Lower	41	16	25	9	1.4	22	0.0
Limits of variation	**Activity -**	**S_u [kPa]**	**S_{ur} [kPa]**	**Sensi-tivity -**	**σ [mS/m]**	**σ_w [mS/m]**	**S [g/l]**
Upper	0.2	26	0.9	72	130	101	0.5
Lower	1.7	8	0.2	17	43	52	0.3

When the soil map and soil investigation data are combined, the Kotka 233 clay can be divided in to sediment layers of the different Baltic Sea phases. Below the dry crust until level of +5 m there is likely a Litorina sediment layer since organic and water contents are high and contrary clay content is moderate. Below that lies probably an Ancylus sediment since the organic content decreases. Clay content is somewhat low for Ancylus sediment (around 50 %) but it is still in the range presented in Table 2.

6.3.6 Masku

Masku site lies in the south-western part of Finland approximately 30 km to the north-west of the Paimio site near the city of Turku. The site locates near railway line between the cities of Turku and Uusikaupunki. Overall Topography of the Masku site is somewhat similar to the Perniö, Sipoo and Paimio where large open areas of clayey soil beds alter with sharp peaks of bedrock hills. Soil profile consist of about 1 m thick dry crust layer underlaying a soft clay layer with thickness of about 11 m. Variable silty/sandy soil layer underlies the clay layer. Site investigations are concentrated on an 8 m thick layer of soft clay between elevations +8–0 m named as Masku clay.

Figure 38 illustrates topography and topsoil formations of the Masku site. Legend is similar with Figure 33. The Masku site lies in a river valley near present river channel. The river valley cuts a continuous post glacial esker (illustrated in green in Figure 38) in to two parts.

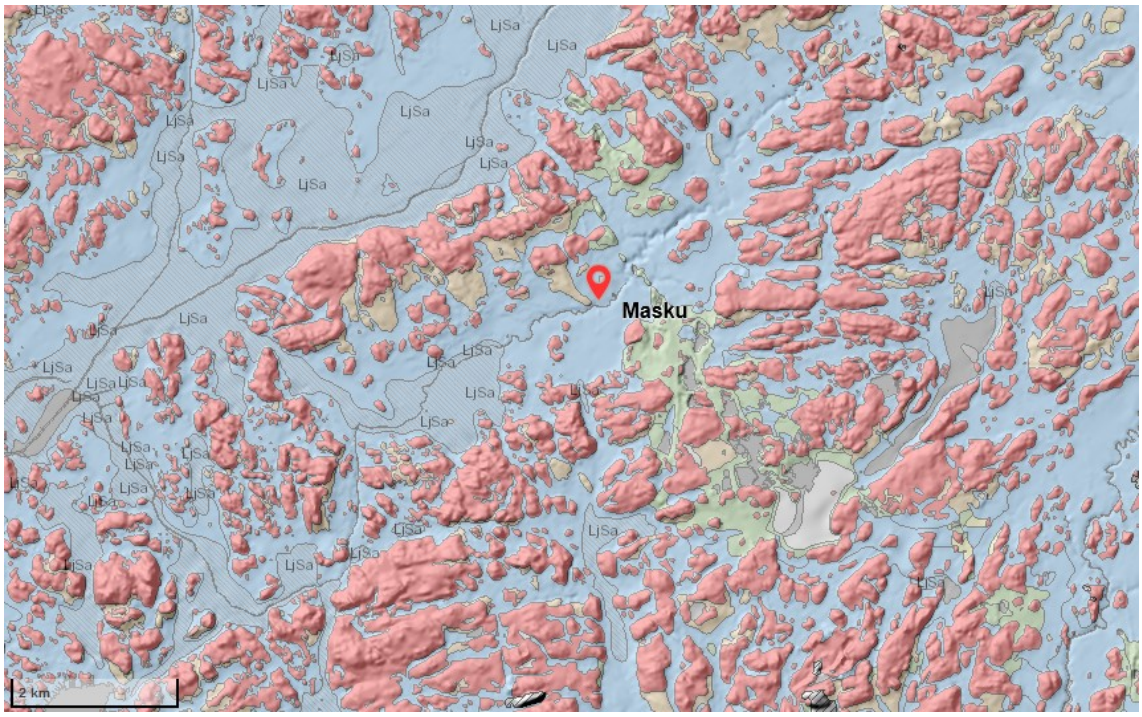

Figure 38. *Topography and topsoil formations of the Masku site (Maaperä ; Rinnevarjostus ; Taustakartta)*

Ranges in the Masku clay properties are shown in Table 9. Investigated part of the Masku clay can be defined as highly plastic moderate sensitive fat clay. Conductivity of the Masku clay seems to be highest of all the sites presented so far.

Table 9. *Ranges of the Masku clay properties.*

Limits of variation	**w [%]**	**PL [%]**	**LL [%]**	**PI [%]**	**LI -**	**Clay content [%]**	**Organic content [%]**
Upper	119	36	97	64	1.4	95	1.7
Lower	63	24	62	36	1.0	60	0.1
Limits of variation	**Activity -**	**S_u [kPa]**	**S_{ur} [kPa]**	**Sensi-tivity -**	**σ [mS/m]**	**σ_w [mS/m]**	**S [g/l]**
Upper	0.7	20	1.5	21	379	-	-
Lower	0.5	15	0.6	18	38	-	-

By combining the soil map and soil investigation data, the Masku clay can be divided to sediment layers of different phases of the Baltic Sea. Below dry crust until level of +5 m there is likely an Ancylus Lake sediment and below that a Yoldia Sea sediment. Probable Baltic Ice Lake sediment underlies these two.

6.3.7 Murro

In early nineties, a highway from the coastal city of Vaasa to central part of Finland to the city of Jyväskylä was decided to build. In the region of Seinäjoki, line of the new highway was about to go over a soft clay deposit for 3.4 km. To be able to evaluate settlements, its speed, and other deformations, Finnish road authorities decided to build instrumented test embankment near the highway line to the area of Murro. To conclude studies, instrumentation and extensive soil investigations were done. Those composed of different kind of soundings (for example Swedish weight sounding (SWT), CPT and CPTU soundings) and sampling with laboratory tests. (Selkämaa 1994) After building the test embankment, data from it and surrounding subsoil is used in several studies (Karstunen & Yin 2010; Koskinen 2014; D'Ignazio 2016).

Figure 39 illustrates overall topography and topsoil formations of the Murro site. It is low lying wide flat area near a river valley. The site has likely been part of a lake in some point of its history. To the south-east of there, the topography rises and becomes more fluctuating with more hills and valleys in small scale. To the opposite direction, the topography stays flatter and not so much variation in height can be seen. Ground surface of the Murro site locates at elevation of +37.7 m. Subsoil of the Murro site consists of a 1.5 m thick dry crust layer underlying a 21 m thick soft soil layer. Until 16 meter depth, soft soil is organic silt and below that lean clay. (Selkämaa 1994; Länsivaara 2001) Site investigations conducted in Fincone project concentrate on first 6 meters of the deposit apart from CPTU soundings which were reached to depth of about 20 m.

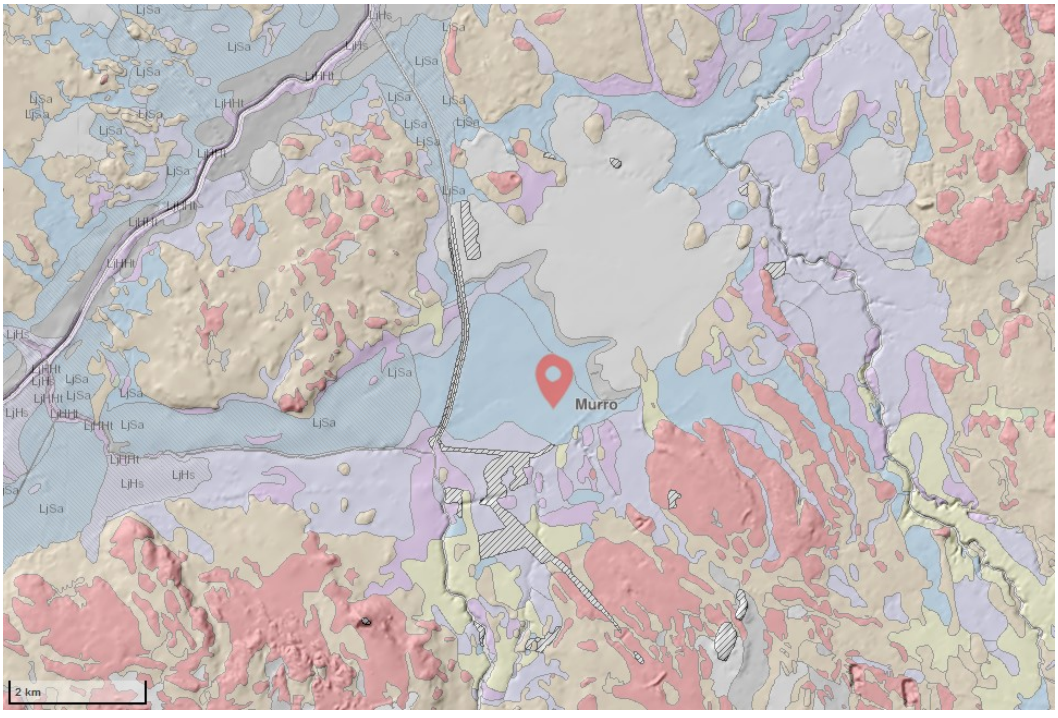

Figure 39. *Topography and topsoil formations of the Murro site (Taustakartta ; Rinnevarjostus ; Maaperä).*

Investigated part of the Murro clay can be defined as higly organic silt. Its plasticity is high and sensitivity moderate. Murro clay differs remarkably from clays of other sites. Due to low clay content and high plasticity, also activity is very high compared to other sites. Ranges of the Murro clay properties are shown in Table 10.

Table 10. *Ranges of the Murro clay properties.*

Limits of variation	w [%]	PL [%]	LL [%]	PI [%]	LI -	Clay content [%]	Organic content [%]
Upper	96	43	94	46	1.5	32.5	3.2
Lower	58	29	54	25	1.1	24.2	1.3
Limits of variation	**Activity -**	**S_u [kPa]**	**S_{ur} [kPa]**	**Sensi-tivity -**	**σ [mS/m]**	**σ_w [mS/m]**	**S [g/l]**
Upper	1.8	28	1.6	27	426	1004	5.7
Lower	1.0	19	0.9	19	84	987	5.5

When the soil map and soil investigation datais combined, the Murro clay can be divide to sediment layers of different phases of the Baltic Sea. Even though, clay content is so low that Murro clay is actually silt, it is probably deposited in Litorina Sea. This is due to that usually sediments in northern Finland are coarser than in south coast.

6.4 Conclusion of the sites

As a conclusion of the sites, it can be said that they represent soft Finnish clays well. Most of the clays are highly plastic with moderate or high sensitivity. Clay content also seems to be high while organic content is in most cases low. Activity seems to be in most cases under 0.5, making clays to be classified as inactive. In some deposits top layers seems to have higher activities that might be explained by formation of more active minerals (Soveri 1950; Gardemeister 1975).

The Murro clay seems to give some difference to the common results. It differs from the other clays in almost every way. Clay content is very low while conductivity and organic contents are high. On the other hand, plasticity is high giving high activity values. The differences might be explained by location (northest of the sites) and sedimentation environment (the Litrorina Sea).

6.5 Assumed errors in field and laboratory tests

Main errors might have occurred in determination of salt content and plasticity properties. Salt content determination is not standard test in TUT geotechnical laboratory so the methods for that had to been developed during these tests. Also the device used to press out pore water was under development throughout the test period and the procedure

changed slightly between the measurements. These both might have effected on the results.

Assumed errors in plastic properties determination might have caused by usage of several operators, since at least the *PL* determination is effected by operator. Also determination of the *LL* might have been erroneous since the settlements even with the lightest cone were very high due to low remolded strengths. Fortunately several tests were conducted around same depths and so the evaluation of the single test quality can be done by comparing it to results near it.

Errors in the field tests relate on the low values of the measured conductivity. Manufacturer promises the conductivity module to work properly on over 50 mS/m conductivities. Presented values are over 50 mS/m, but those are temperature corrected. The real measured values were on some of the sites under 50 mS/m. Effect of that is not easy to evaluate, since another test method for conductivity measurements was not available.

7. CORRELATIONS BETWEEN ELECTRICAL CONDUCTIVITY AND GEOTECHNICAL PARAMETERS

In this chapter relations between soil conductivity and geotechnical parameters are shown and discussed. Correlations were mainly looked from results combined of all the sites. In addition, water content results are divided into groups of certain Baltic Sea phase, and correlation is tried to find also inside these groups.

Firstly, correlation of soil conductivity and parameters describing soil composition is tried to find. On that way, it is tried to find out what controls the soil conductivity. Secondly, correlation between soil conductivity and plasticity parameters is tried to find. Thirdly, correlation between soil conductivity and strength parameters is looked for.

These kind of correlations have not been done for Finnish clays, except for limited data provided by (Törnqvist et al. 2001). On the other hand, for Norwegian clays some correlations have been tried to find (Long et al. 2012; Montafia 2013). Main conclusion of Montanfia (2013) was that soil salinity defines soil conductivity when the salinity exceeds 1 g/l. Below that, effect of salinity becomes arbitrary. However, factor, replacing salinity, could not be identified.

Long et al. (2012) found clear and strong correlation between soil conductivity and pore water salinity. Also clay content seemed to increase soil conductivity. Remolded shear strength and plasticity index were concluded to increase with increasing conductivity.

7.1 Correlations to parameters describing soil composition

Figure 40 illustrates correlation between water content and soil conductivity. As it can be seen from the figure, no clear general correlation can be found.

The data is grouped in different scales of soil conductivity. Triangles represents results with soil conductivity < 150 mS/m, squares are for results with soil conductivity between 150–225 mS/m, and circles represent results with soil conductivity over 225 mS/m. Clays Sipoo, Paimio, Kotka 233, and top parts of Perniö belong to the triangle group while Kotka 238 and lower parts of Perniö are in the square group. The Murro and Masku clays belong to the circle group. Inside these groups, weak correlations can be seen between soil conductivity and water content. It also seems that when the scale of the soil conductivity increases, soil conductivity changes strongly with water content.

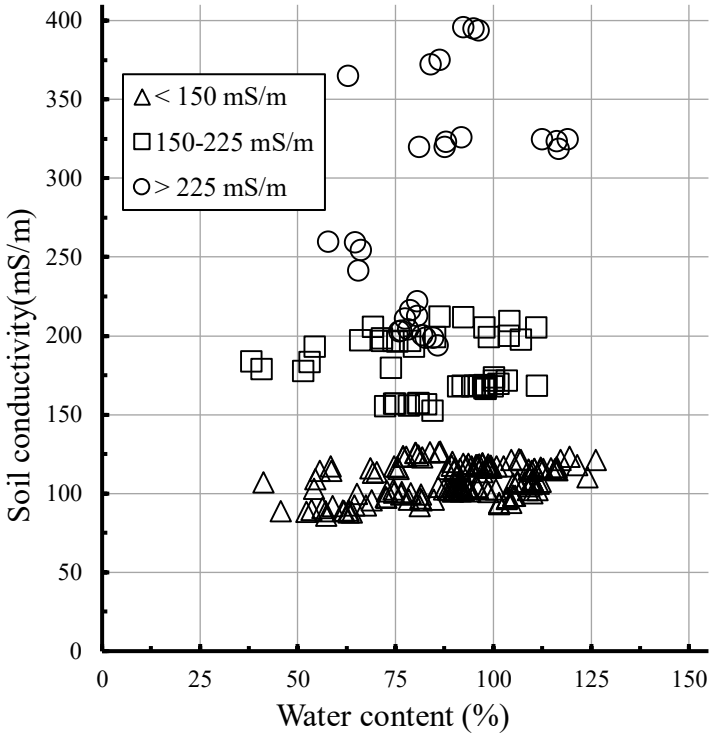

Figure 40. *Correlation between soil conductivity and water content.*

In Figure 41, water content against soil conductivity is plotted. In the figure, data is grouped so that results of the evaluated Baltic Sea phases are separated. Green triangles refer to the Litorina Sea sediments, red squares to the Ancylus Lake sediments, and blue spheres for the Yoldia sea sediments. Again no clear correlation exists in any of the groups.

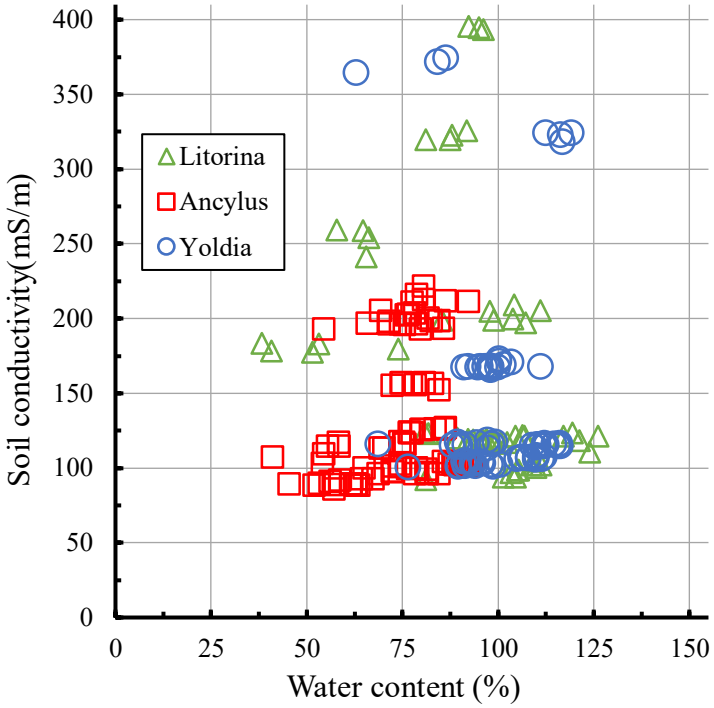

Figure 41. *Correlation between soil conductivity and water content grouped based on sedimentation environment.*

In Figure 42, clay content and soil conductivity data is plotted. Based on the figure, no correlation exists between these two.

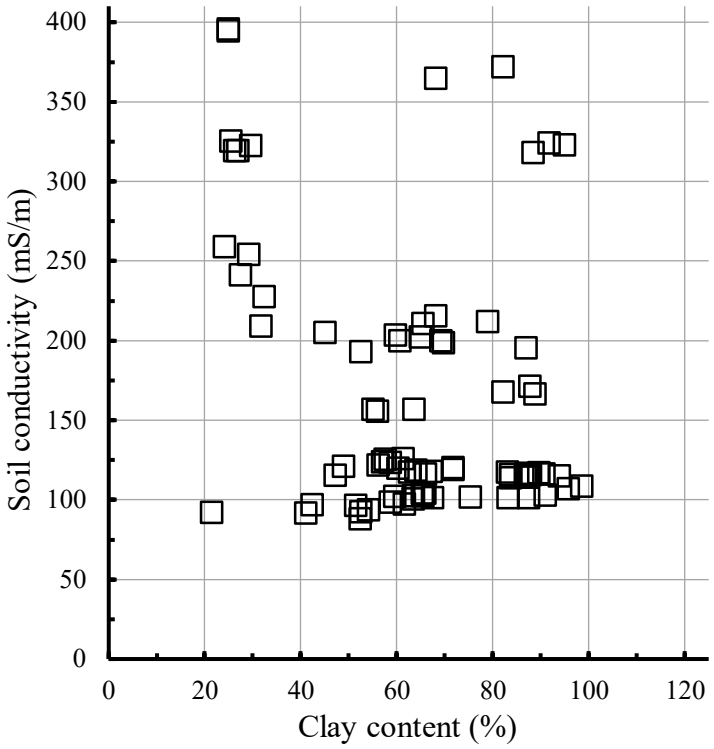

Figure 42. *Correlation between soil conductivity and clay content.*

Figure 43 illustrates correlation between pore water and soil conductivity. This figure contains data from all the sites except for Masku, since pore water conductivity was not determined there. As it can be seen from the figure, a clear and strong correlation between these two can be found. The figure shows also the equation of the linear trend line fitted to the results and coefficient of determination of that.

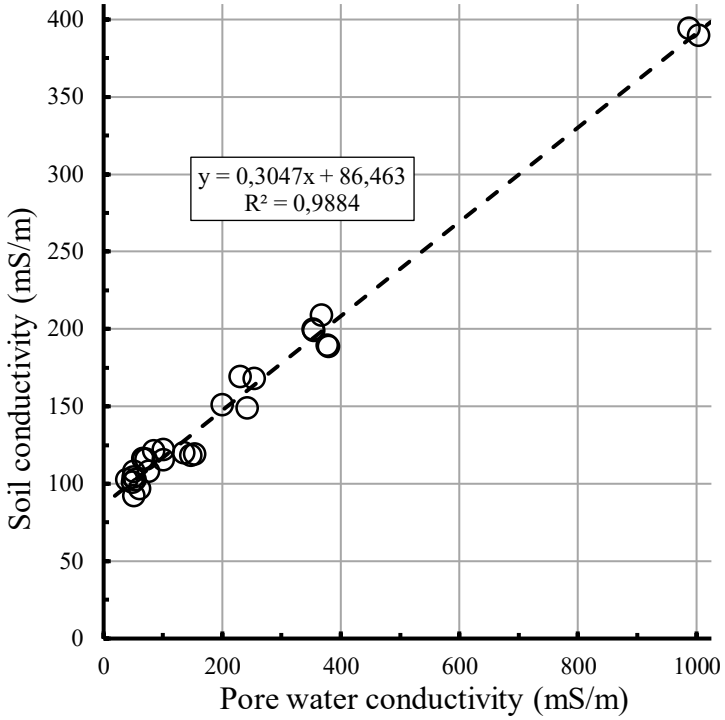

Figure 43. *Correlation between soil and pore water conductivity.*

Correlation between soil conductivity and pore water salinity can be seen from Figure 44. As pore water conductivity basically expresses pore water salinity, similar relation as in Figure 43 exists.

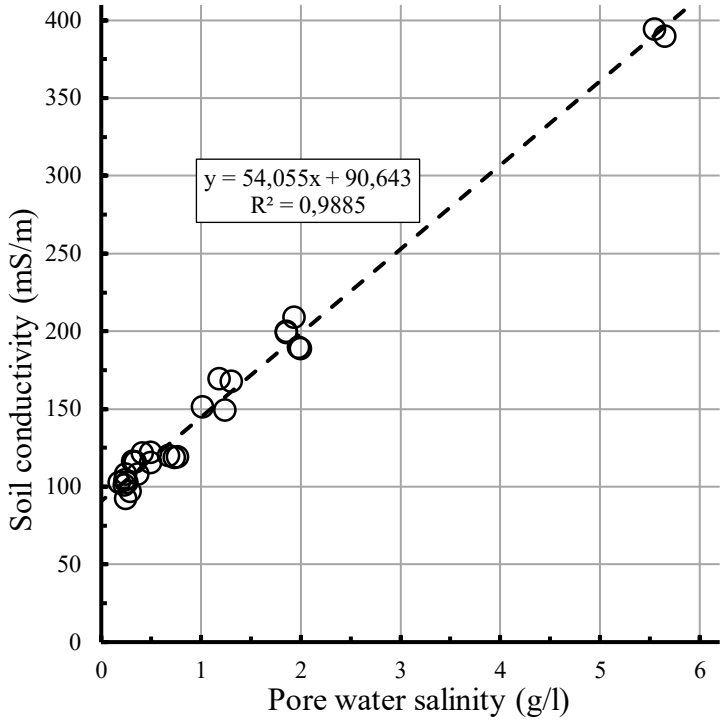

Figure 44. *Correlation between soil conductivity and pore water salinity.*

Based on the soil composition correlation results it seems that pore water conductivity controls the soil conductivity entirely. In more detail, pore water conductivity describes salinity of the pore water which controls the soil conductivity. On the other hand, water and clay content seem to have very little effect on soil conductivity.

When water content is grouped in different scales of soil conductivity, slight correlations can be found. As the soil conductivity scale increases, water content seems to correlate with soil conductivity better. On the other hand, when the water content and soil conductivity data is grouped based on evaluated sedimentation environments, no correlations in these groups can be found.

7.2 Correlations to plastic properties

Figure 45 illustrates relation between plasticity index and soil conductivity. In here results are divided in two different groups. Squares refer to results with soil conductivity under 150 mS/m while circles represent results with soil conductivity over 150 mS/m.

Square group does not show any correlation. On the other hand, in circle group very weak positive correlation can be seen even though variation is high. Also, some kind of lower limit for *PI* with certain soil conductivity could be sketched.

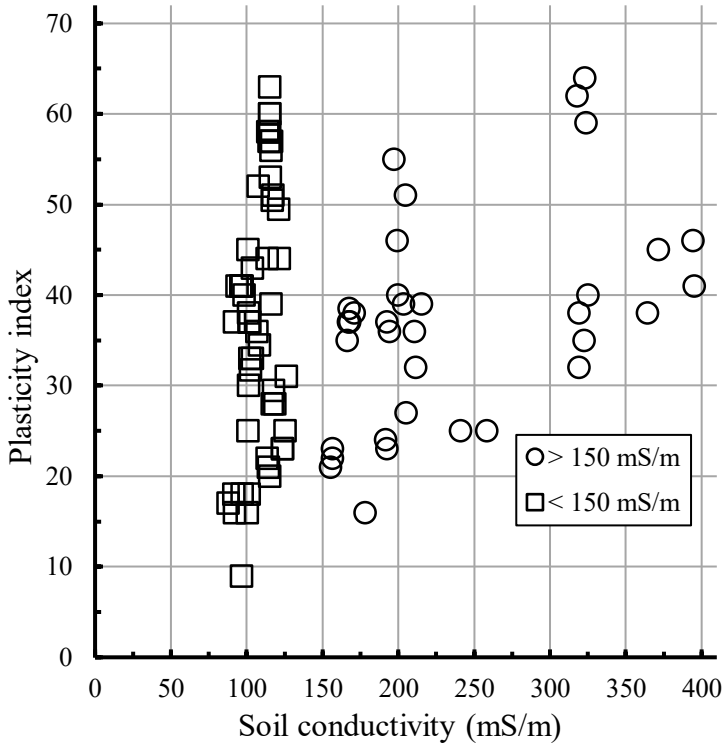

Figure 45. *Correlation between soil conductivity and plasticity index*

In Figure 46, relation between liquidity index and soil conductivity is shown. Again results are divided in two groups. Squares illustrate results with soil conductivity under 150 mS/m and circles are for over 150 mS/m results.

For square group no correlation can be seen. Instead, for the circle group some kind of trend can be seen. Correlation for that is not linear but liquidity index seems to decrease curvilinear as the soil conductivity increases, and upper limit for *LI* in certain soil conductivity can be evaluated.

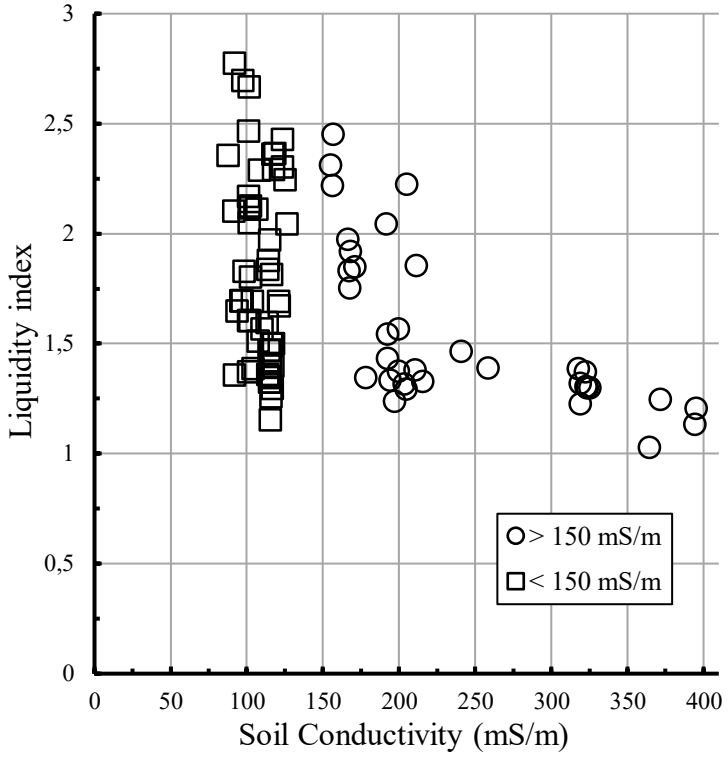

Figure 46. *Correlation between soil conductivity and liquidity index.*

Figure 47 illustrates relation between activity and soil conductivity. Similar division is made for the results as in Figure 46. For square group no correlation exists. While, circle group shows some kind of increase in activity with increasing soil conductivity.

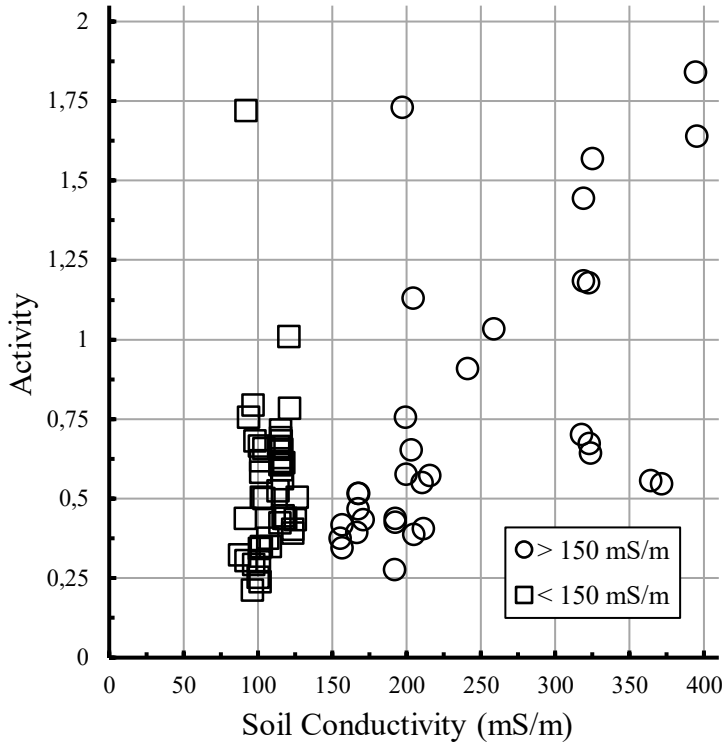

Figure 47. *Correlation between soil conductivity and activity.*

As a conclusion of the soil conductivity correlations with the plastic properties, it can be said that plasticity index seems to correlate with soil conductivity at some level and lower limit for *PI* as a function of soil conductivity can be determined. Also, a curvilinear negative correlation exists with liquidity index and faint positive correlation with activity. In the case of activity, variation seems to be high.

7.3 Correlation to strength properties

Figure 48 illustrates relation between soil conductivity and intact undrained shear strength. No correlation can be seen between those.

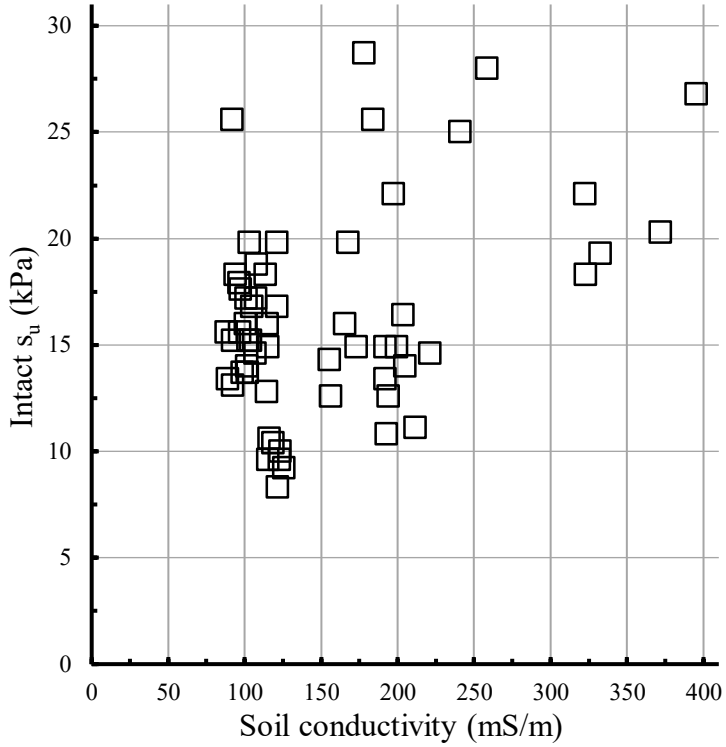

Figure 48. *Correlation between soil conductivity and intact undrained shear strength.*

In Figure 49, relation between soil conductivity and remolded undrained shear strength is shown. Division into two groups is made on similar basis as in previous figures. For square group no correlation exists. With higher soil conductivity, there seems to be positive correlation. However, variation in that is high.

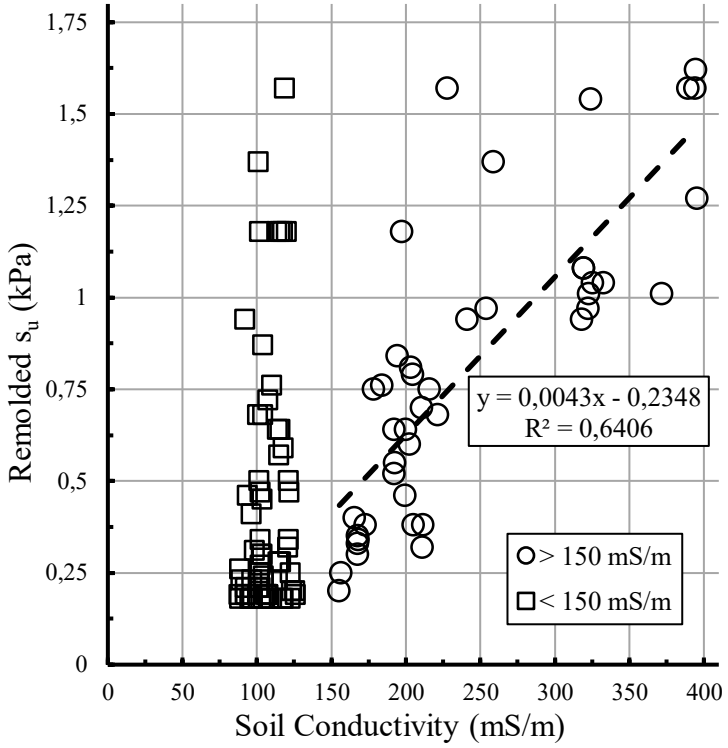

Figure 49. *Correlation between soil conductivity and remolded undrained shear strength.*

Figure 50 illustrates correlation between soil conductivity and sensitivity. For low soil conductivity results no correlation can be seen. On the other hand with higher conductivities (circles), similar decreasing correlation can be seen as with *LI* in Figure 46.

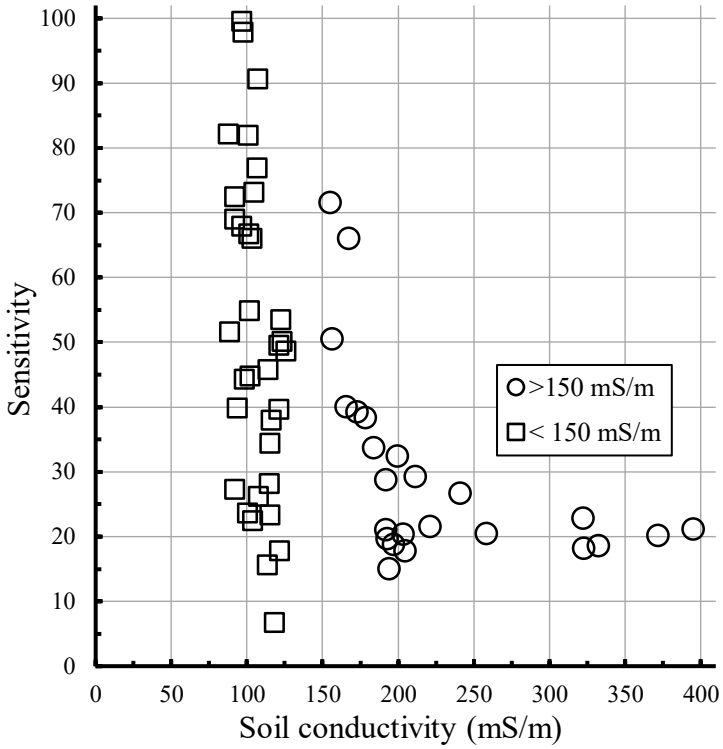

Figure 50. *Correlation between soil conductivity and sensitivity.*

As a conclusion of strength results and those correlations to soil conductivity, it can be said that intact strength does not seem to correlate with soil conductivity. On the other hand, remolded strength seems to have positive correlation with soil conductivity. Also sensitivity seems to decrease with increasing soil conductivity.

7.4 Discussion of the results and comparison to other studies

Of soil composition parameters, pore water conductivity seems to have greatest effect on soil conductivity. While water content and clay content does not seem to have any effect on it. This might be due to fact that as the water content is very high and all the tested samples were fully saturated, pore water conductivity is the most controlling part of the soil conductivity since there is simply so much of pore water. As said before, in more detail the pore water conductivity can be assumed to describe pore water salinity when it controls conductivity of the tested clays. Even though mineralogy of the samples were not examined, the correlation between pore water and soil conductivities is so strong that previous assumption can be made. Variation seen in this correlation might be due to different ionic compositions of the pore water electrolyte that may give different responses.

When the correlation between the soil and pore water conductivity is so strong it is interesting to see how it correlates with plasticity and strength parameters. On previous studies (Bjerrum 1954; Rosenqvist 1955) clear correlations between electrolyte concentration of the pore water and mechanical properties of the soil can be found. Mainly effects were seen in increasing plasticity and higher remolded strengths. Similar findings were done in this thesis for remolded strength even though clays with different pore water conductivities were mainly from different sites. However, *PI* does not seem to correlate very strongly with conductivity.

In addition, it would have been interesting to see how the ratio $\alpha = s_u / \sigma'_p$, where σ'_p denotes for pre consolidation pressure, changes with conductivity. This has been found to increase with increasing pore water salinity in previous studies (Bjerrum 1954; Rosenqvist 1955)

Effect of increasing pore water salinity to plasticity and strength properties comes from the effects related to the DDL and its effect on forces acting between clay particles as discussed in previous chapters. Variation seen in results can be explained by variation of the tested clays. Even though clay and water contents nor mineralogy does not seem to effect on the soil conductivity, they might explain different behaviors of soils with different pore water salinities.

Compared to other studies (Long et al. 2012; Montafia 2013), more clear effect of the pore water salinity/conductivity to soil conductivity was found. Results are compared in Figure 51. In that measured conductivity seen in Figure 44 is transformed to resistivity to ease comparison. Differences seen in results might be due to different composition, geological history and pore water composition of the tested clays. Also differences in interpretation of the pore water salinity might have effected on results. Further on, soil resistivity is in much narrower range in the clays of this thesis compared to the other publications. This might influence on relation seen in the figure. However, over all image in all the plots is very similar, an exponential decrease of resistivity with increasing salinity.

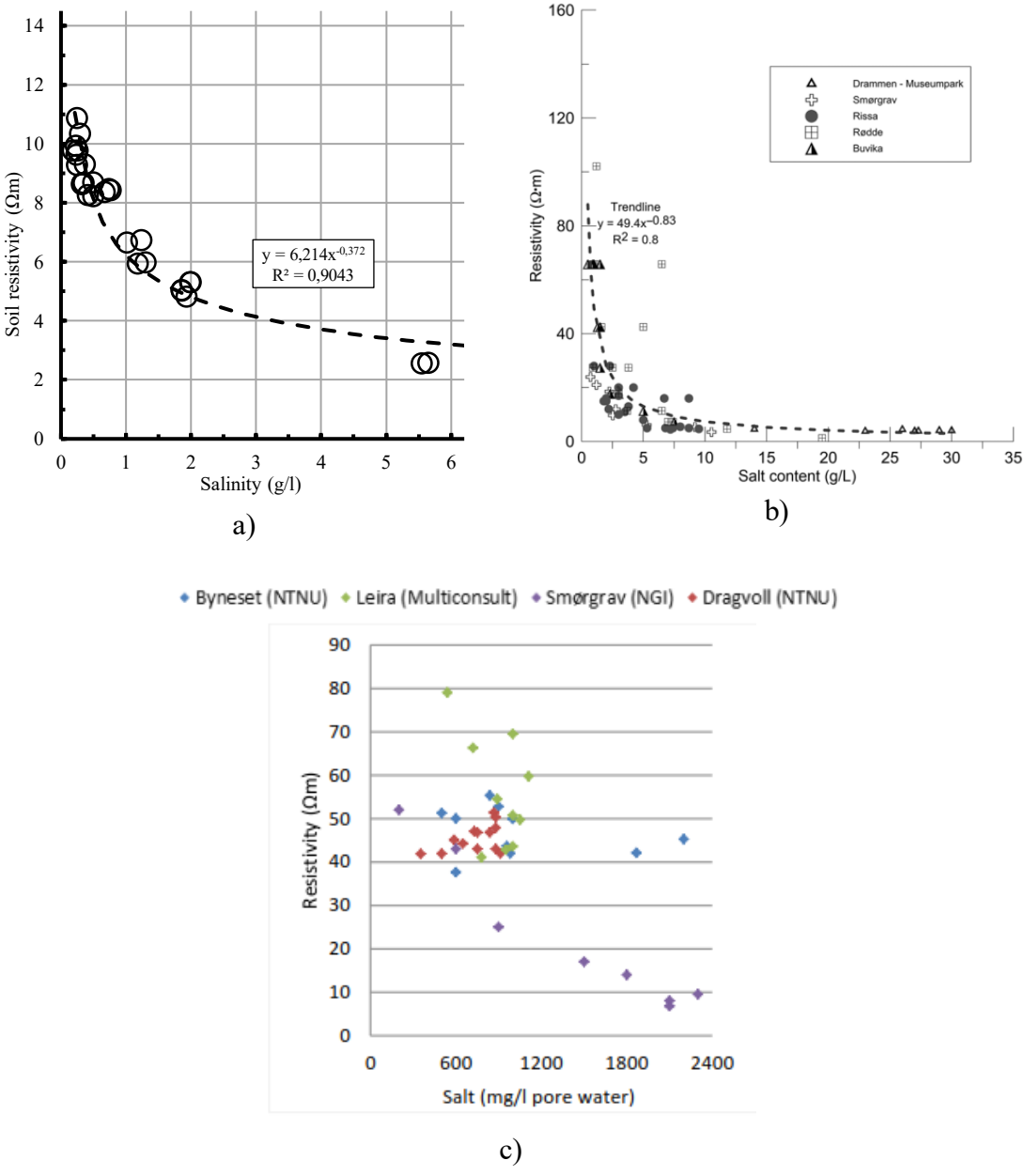

Figure 51. *Comparison of resistivity versus salinity plots a) this thesis, b) (Long et al. 2012, p. 1162), and c) (Montafia 2013, p. 48).*

Similarly to this thesis, Long et al. (2012) and Montafia (2013) could not found clear correlation between water content and soil conductivity. Comparison of results is shown in Figure 52 where conductivity of Figure 40 is transformed to resistivity. Clearest correlation seems to found from results of Montafia (2013), but there the water content range is quite limited and much lower compared to Finnish clays of this thesis. Results of Long et al. (2012) show high variation and no correlation exists as in results of this thesis.

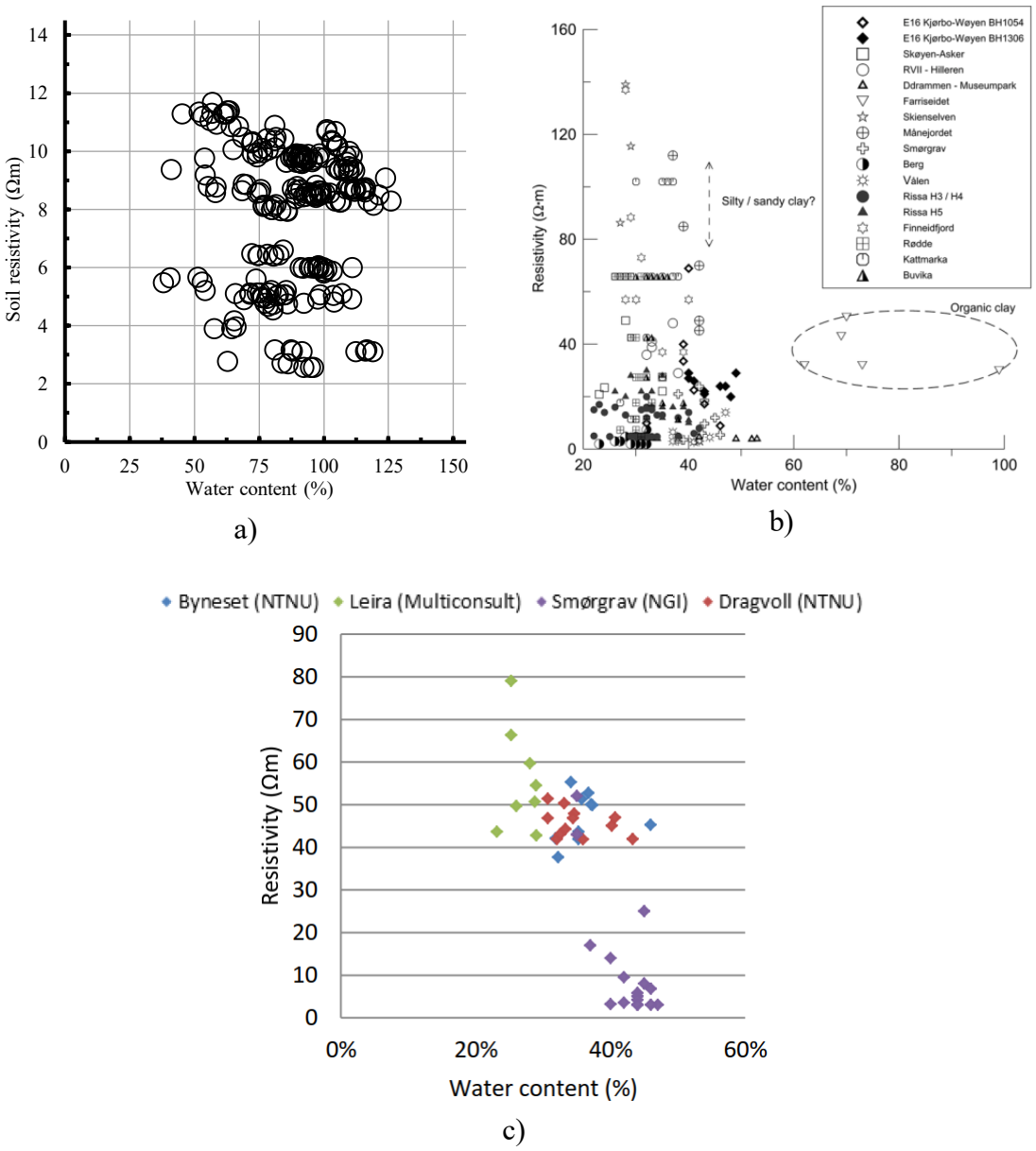

Figure 52. *Comparison of resistivity versus water content plots a) this theisis, b) Long et al. (2012, p. 1165), and c) Montafia (2013, p. 49).*

Comparison to results of Norwegian clays gives good reference to results of this thesis even though Norwegian clays differ from Finnish ones. Main difference is that Norwegian clays are truly marine origin with high original pore water salinity while Finnish clays are formed in more of a lacustrine environment with low or moderate pore water salinities. This gives some fundamental differences for these clays causing the differences in properties controlling conductivity.

Based on experimental results, electrical conductivity measurements cannot be used for determination of water content. Even a site specific relation between water content and conductivity cannot be determined, since the pore water conductivity seems to control the soil conductivity and variations in it seems to be very high even inside one site. This is an opposite conclusion compared to publication Törnqvist et al. (2001), where an exemplified relation between water content and resistivity is shown

Major problems in relation to building reliable correlations described in this chapter is due to lack of data. As said before no data was available through the whole deposits but from discrete depths of somewhat homogenous layers. Other source of the lack of data is insufficient determination of the mineralogy of the clays. The mineralogical determination was not done to the sites due to lack of time. Finally, pore water composition was not determined from the sites. These two determinations would have probably helped to explain variation seen in relations. However, even those might not have helped in finding a correlation between water content and electrical conductivity.

Clear and strong correlation between soil conductivity and pore water salinity was found. This makes interesting to study if the soil conductivity measurements are usable for evaluation of corrosion environments in soils. For example in case of steel piles, corrosion has a great effect on design. Even though, maybe no straight numeric value of the amount of corrosion cannot be made based on conductivity measurements, it might help to concentrate the sampling to the most interesting layers on a site. In addition, soils contaminated with inorganic salts could be observed using conductivity measurements.

8. CONCLUSIONS

In this thesis, a method to determine water content of soft Finnish clay with electrical conductivity measurement was tried to find. Through a literature study and experimental tests, factors affecting to this relation was tried to determine.

Clay particles are usually very small platy like constructions. Basic building blocks of clay minerals are silica tetrahedron and aluminum or magnesium octahedron sheets. Minerals compose of these sheets attached to each other by dividing some atoms. These structures are smallest units of specific minerals and are called unit cells. During formation of these unit cells, some of the usual atoms are replaced with others, making unit cells electrically charged. This is called isomorphous substitution. Since the substituted atoms have usually lower valence than the original ones, the charge is negative and is balanced with cations surrounding the unit cell. Minerals can be identified based on the unit cells, but also interaction and bonding of these unit cells effects on behavior of minerals. The balancing cations cause ionic bonds between unit cells, but interaction between them can also be result of van der Walls forces or hydrogen bonds.

Isomorphous substitution makes clay particles electrically charged, and cations surround the particle to enable electrical balance. In water, the cations tend to move away from the particle surface due to diffusion, and they are simultaneously dragged back to the surface because of electrostatic force. This causes atmospheric distribution of the cations around a clay particle called DDL (diffusion double layer). Size of the DDL changes with the pore water salinity shrinking with increasing salinity. This effects on the interaction between clay particles causing different clay structures, plasticity and strength behavior. As the DDL contains ions of the pore water, it has effect on the electrical conducting phenomenon that is in soils governed by ionic conduction.

Formation of soil is a part of so called geologic cycle, in which rock and soil forms out of magma and melts when it falls back under the Earth crust. Most of the Finnish clays are formed through sedimentation. The sedimentation process can be divided into three parts, which are erosion, transportation, and sedimentation. In erosion, flows of fluids detach particles from rock or soil formations when in transportation those particles are moved by those flows. To happen, both of these phenomena needs high enough flow energies, and when this energy becomes too low, the particles starts to settle and form sediment deposits. Depending on the eroding and transporting flows, particles are sorted out differently. In case of clay deposits, flows have to slow down steadily to be able to sort out large particles from small clay particles. Also sedimentation environment have effect on deposit. For example changes in salinity, temperature or pH might tend to flocculate some particles, making them to settle. After sedimentation particles are not in a static state but several factors effect on them. For example, ground water percolation and

changes in ground water table effect on the sediments in a deposit causing changes in plastic and strength properties.

Finnish clays are formed mainly during and after last glacier called Weichselian. Its end is located to somewhat 10,000 years from now. Most of the Finnish clays are formed into the Baltic Sea basin, which formed to bedrock depression caused by compression of continental ice sheet. Changes in the Baltic Sea basin were huge causing variable environments for clays to settle. The Baltic Sea changed from lake to sea many times but usually the salinity was only moderate also in the sea phases. Different phases gave different properties for sediments deposited to those. Some of those properties are very distinguishing for certain phase while others are more similar. These properties can be used to identify sediments of certain phase, but is difficult using geotechnical tests only. While there were significant changes in the sedimentation environment, the mineralogical composition of Finnish clays is in most cases uniform containing mostly low active illite and chlorite.

Electrical conductivity of soil, like other conductivities, can be expressed in a form of the Ohms law. On the other hand, since soil is a media composed of several different phases, the conduction phenomenon of it is very complex. The famous Archie's law forms a basis for modelling electrical conductivity of soil. In pursuance of it, conductivity of soil is related to conductivity of its pore water. Coefficient combining these two is called formation factor, since it was found to change along different formations. Later on it was found that clayey soils do not follow this kind of relationship, but the clay particles effect on the conduction phenomenon. To take into account for these effects, models containing multiple conductors were developed.

Measurement of electrical conductivity of soil is based on feeding current to soil and measuring potential difference in two points in the soil. Then based on the Ohms law, the conductivity can be determined. Since the soil does not usually form conductor of certain shape, the volume where the current flows must be evaluated. Based on order of the measuring electrodes, the geometrics of the current flow can be evaluated. Probe method, used with CPTU measurements in this thesis, uses mostly Wenner array for electrodes. There the current is fed to the soil through the outermost electrodes while the potential difference is measured with inner ones.

Electrical conductivity is not a constant value of soil but depends on several factors. Temperature effects on pore waters viscosity and through that to mobility of ions in it. This makes soil electrical conductivity temperature dependent. Effects of different temperatures between site and laboratory tests are usually taken into account by correcting measured values to same reference temperature (25 °C). As soil conductivity is usually measured using alternating current, it is dependent on measuring frequency. This is due to electrode polarization but also DDL effects on it. When the frequency is increased in high enough values, a phenomenon called DDL relaxation occurs increasing conductivity.

When the above mentioned conditions are kept constant, electrical conductivity of soil depends on itself. Based on models developed for soil conductivity, it can be said that amount of pore water and conductivity of it controls the soil conductivity. Also soil structure in different scales, mineralogical composition, amount of clay, and pore waters ionic composition effects on relation between pore water and soil conductivities.

Experimental part of this thesis composed of field tests, with electrical conductivity module used with CPTU, and laboratory tests. In laboratory, several index parameters were determined along with strength parameters determined with fall cone test. In addition to basic geotechnical index testing, pore water conductivity and salinity were determined. These tests were made for seven sites of soft clay deposits. The sites located in the southern part of Finland except for the Murro site. Pore water conductivity were determined from all of them except for the Masku site. Tested clays were in general soft and highly plastic with moderate to high sensitivity. Clay contents were in most cases over 50 % and pore water salinities were in general between 0.3–2.0 g/l. However, the Murro site differs from others firstly by its location and secondly by its soil properties. The Murro site is the northernmost of all the sites lying in Ostrobothnia and its soil composes mostly of organic silt with high (around 5.5 g/l) pore water salinities.

Correlations between laboratory measured properties and soil conductivity were determined. Most defining correlation found was the one between pore water and soil conductivity. Based on results, it seems that pore water conductivity determines soil conductivity of soft Finnish clays. In addition no clear general correlation between water content and soil conductivity could be found. However, when water content data is grouped with different scales of soil conductivities, it seems that some kind of correlation exists. In order to confirm that, more tests using high conductivity clays should be done. Of plasticity and strength properties, plasticity index and remolded undrained shear strength seem to have weak positive correlations with soil conductivity. In addition, liquidity index and sensitivity seems decrease with increasing soil conductivity, and some kind of upper limit of those as a function of soil conductivity can be determined. Findings made of plasticity and strength properties are in line with previous studies and the DDL theory presented in this thesis. However, the main goal of this thesis, to find a way to determine water content through electrical conductivity measurements, was not achieved.

Since the correlation between pore water and soil conductivity was found to be so clear and strong, and as the pore water conductivity is mainly a measure of its salinity, future research could concentrate on studying corrosion environments with conductivity. This would help on getting preliminary results of the corrosion environment and concentrating sampling to the most interesting layers. In addition, soil conductivity measurements could be also used for finding soils contaminated with inorganic salts.

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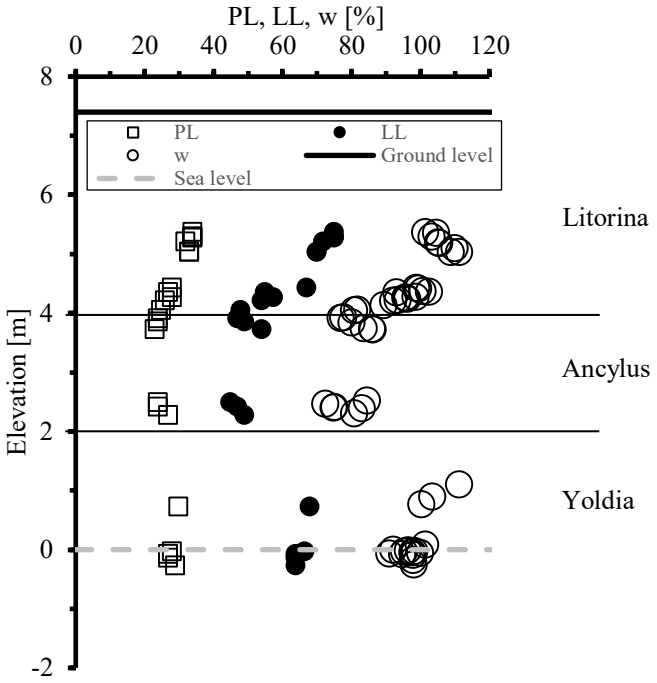
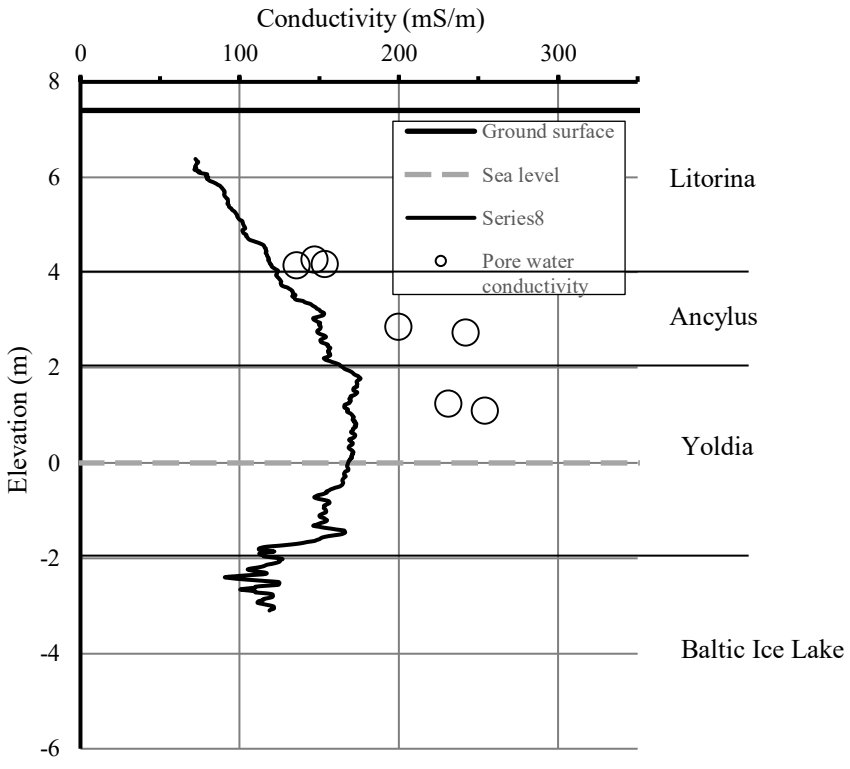
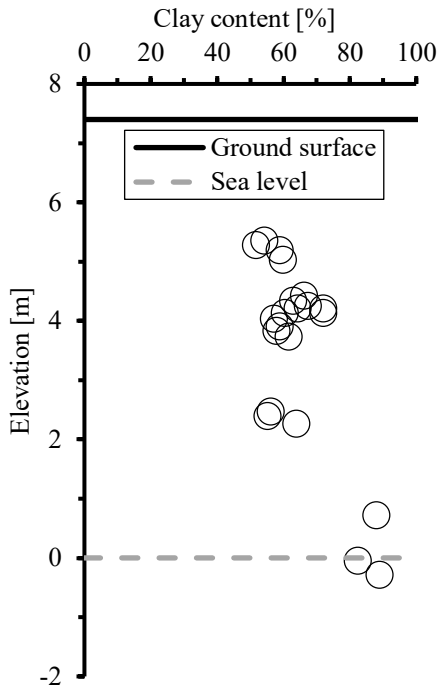
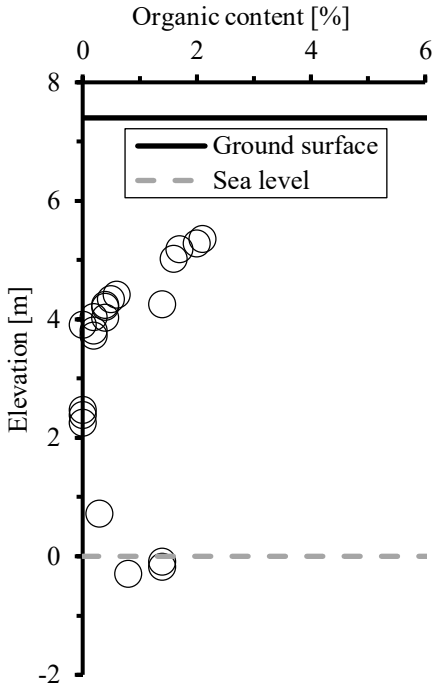
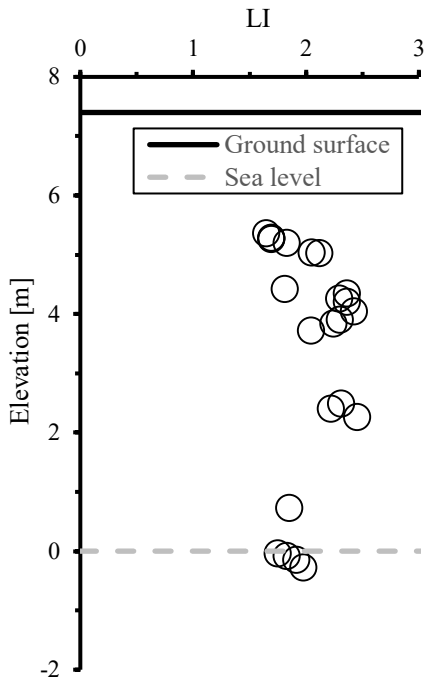
APPENDIX A: PERNIÖ SITE INVESTIGATION RESULTS

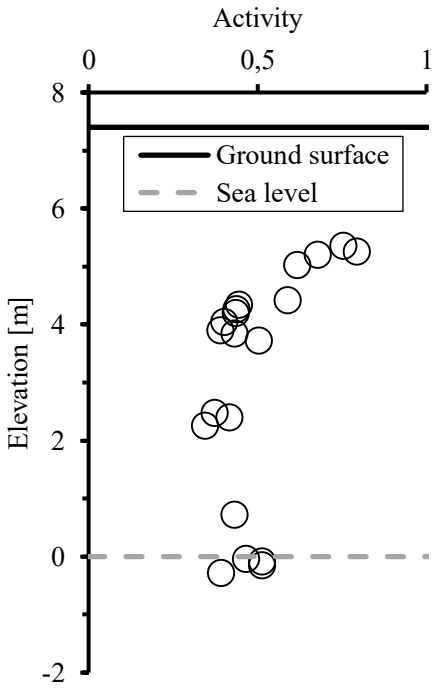


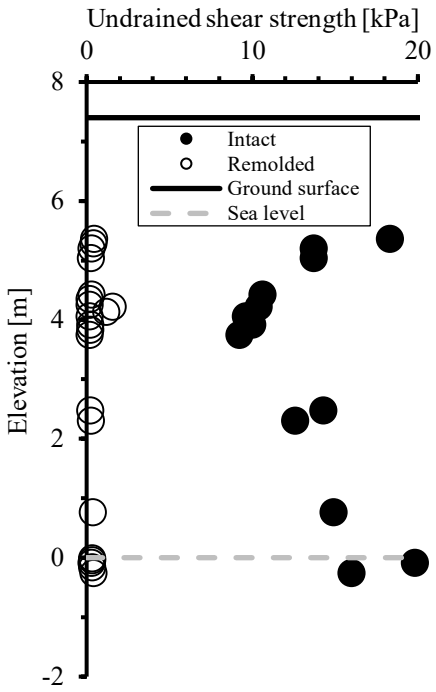


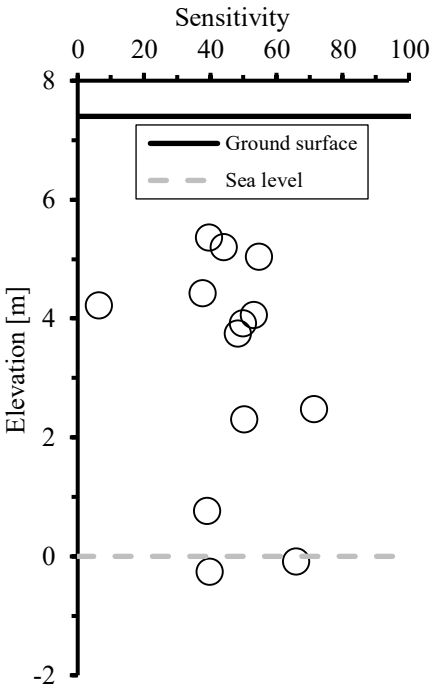

Clay content [%]
0
20
40
60
80
100
8
6
4
2
0
-2
Elevation [m]
Ground surface
Sea level

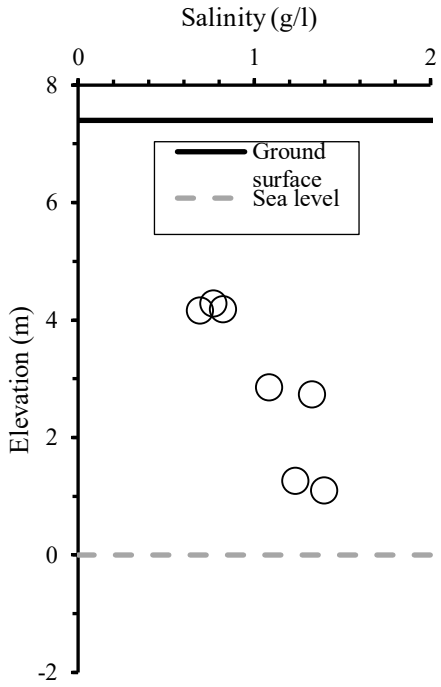

Organic content [%]
0
2
4
6
8
6
4
2
0
-2
Elevation [m]
Ground surface
Sea level


LI
0
1
2
3
8
6
4
2
0
-2
Elevation [m]
Ground surface
Sea level

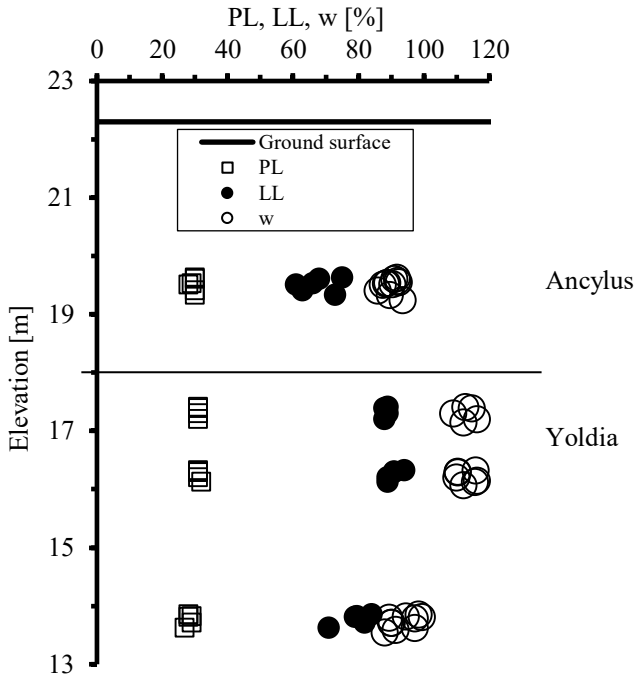

Activity
0
0,5
1
8
6
4
2
0
-2
Elevation [m]
Ground surface
Sea level

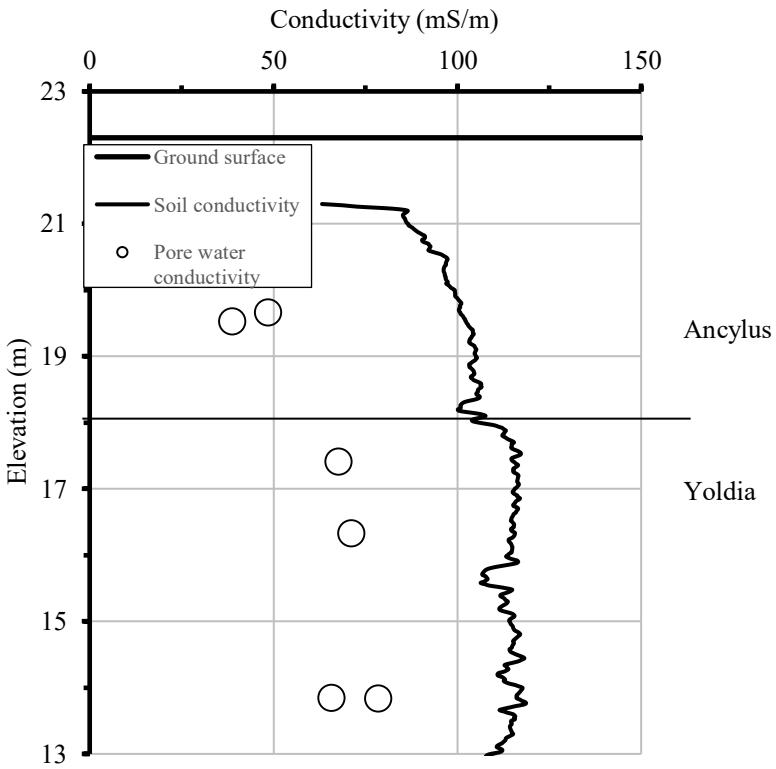

Undrained shear strength [kPa]
0
10
20
8
6
4
2
0
-2
Elevation [m]
Intact
Remolded
Ground surface
Sea level

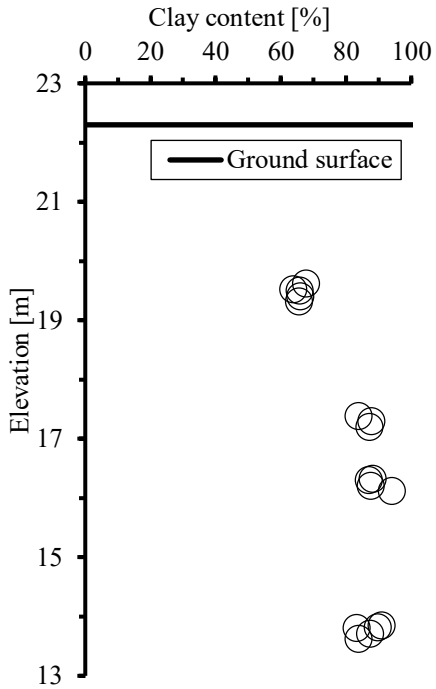

Sensitivity
0
20
40
60
80
100
8
6
4
2
0
-2
Elevation [m]
Ground surface
Sea level

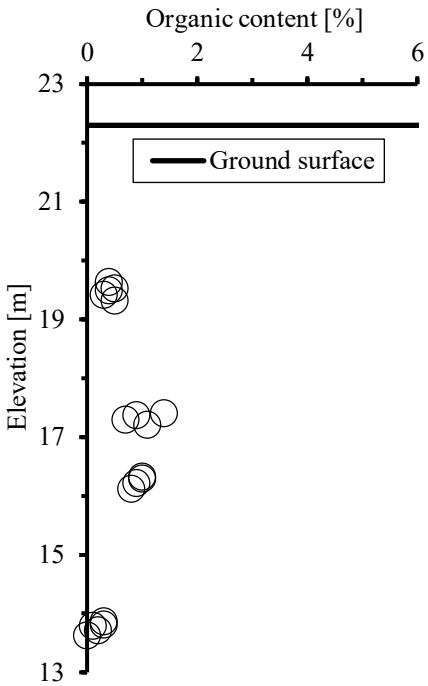

Salinity (g/l)
0
1
2
8
6
4
2
0
-2
Elevation (m)
Ground surface
Sea level

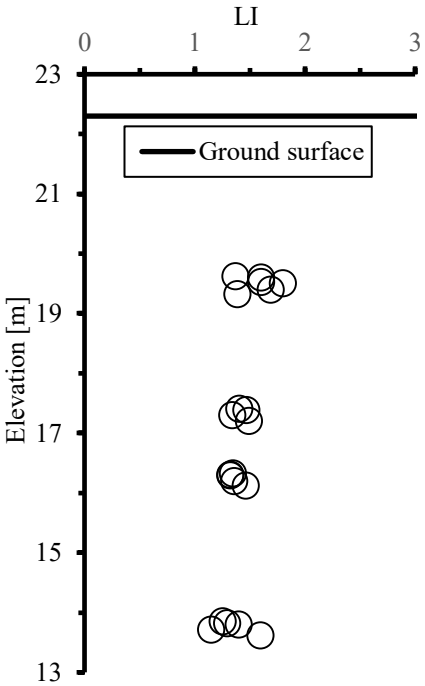
APPENDIX B: SIPOO SITE INVESTIGATION RESULTS

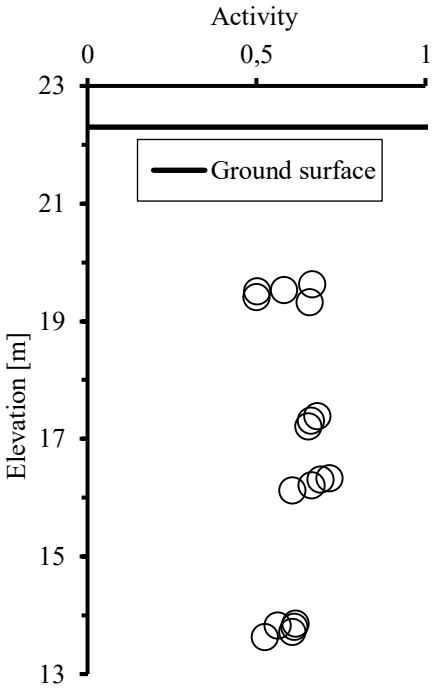


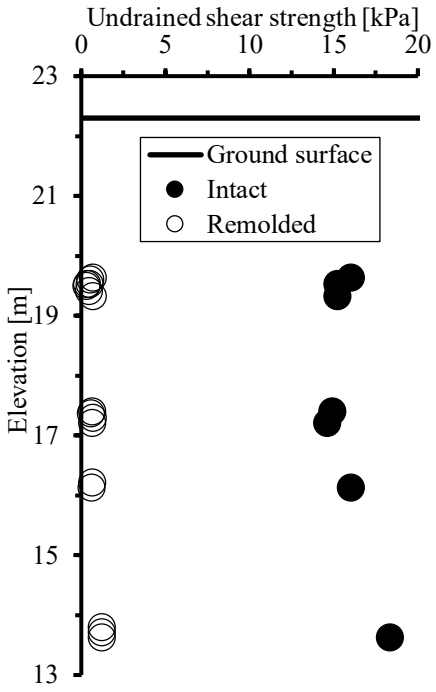


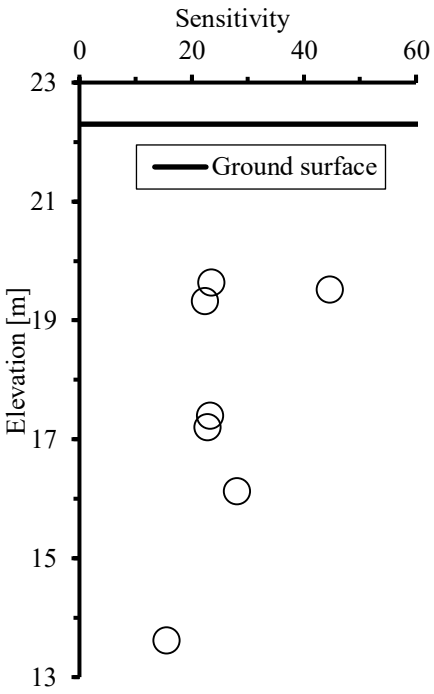

Clay content [%]
0
20
40
60
80
100
23
21
19
17
15
13
Elevation [m]
Ground surface

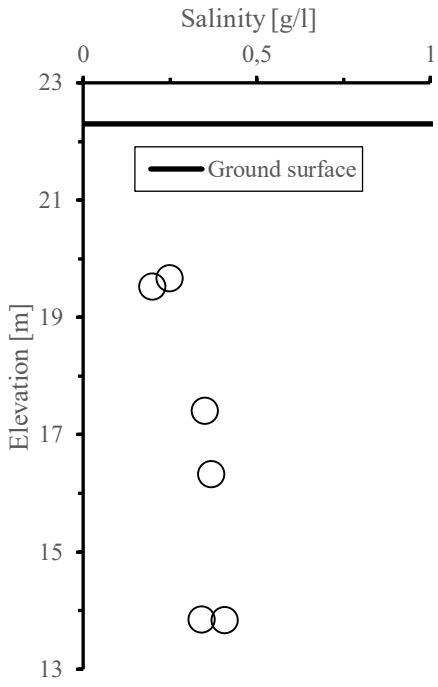

Organic content [%]
0
2
4
6
23
21
19
17
15
13
Elevation [m]
Ground surface


LI
0
1
2
3
23
21
19
17
15
13
Elevation [m]
Ground surface

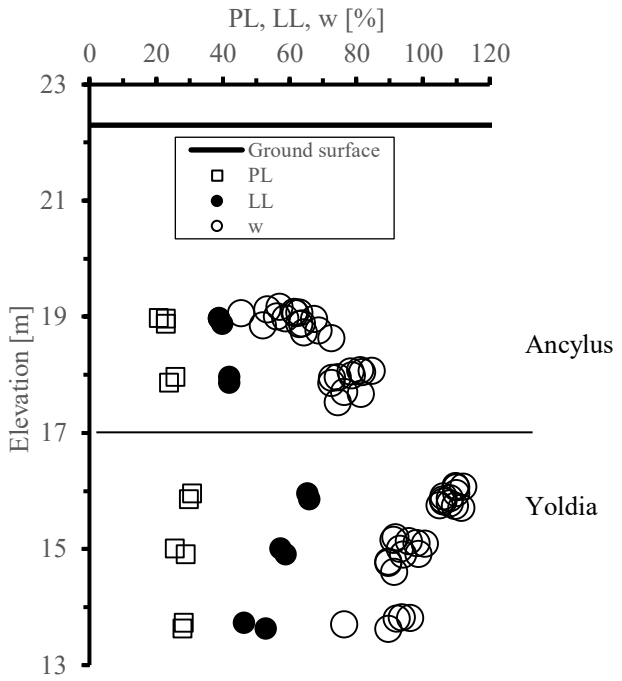

Activity
0
0,5
1
23
21
19
17
15
13
Elevation [m]
Ground surface

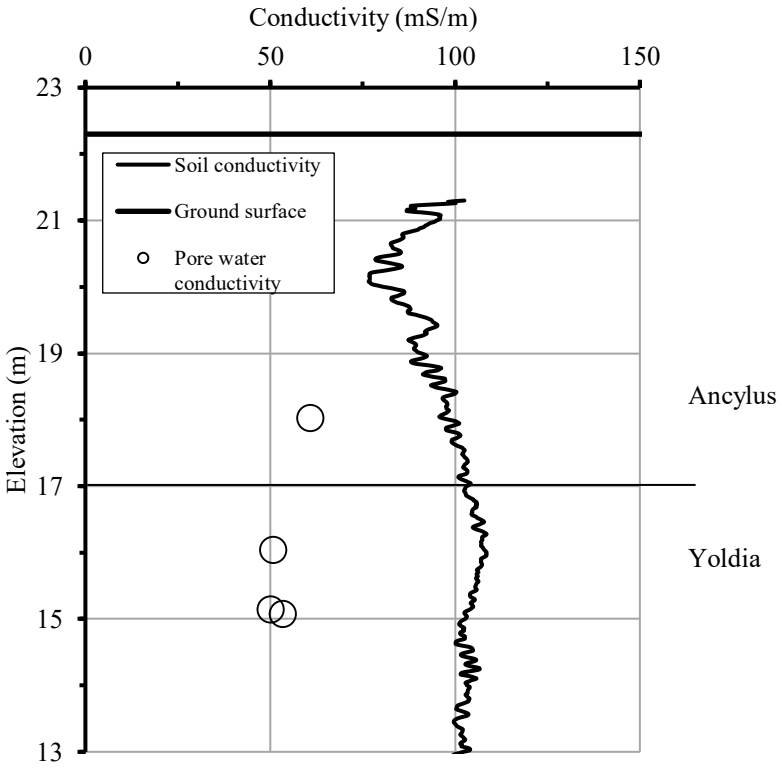

Undrained shear strength [kPa]
0
5
10
15
20
23
21
19
17
15
13
Elevation [m]
Ground surface
Intact
Remolded

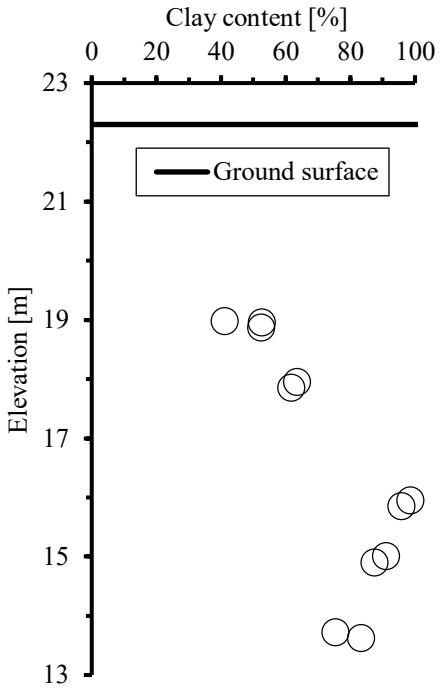

Sensitivity
0
20
40
60
23
21
19
17
15
13
Elevation [m]
Ground surface

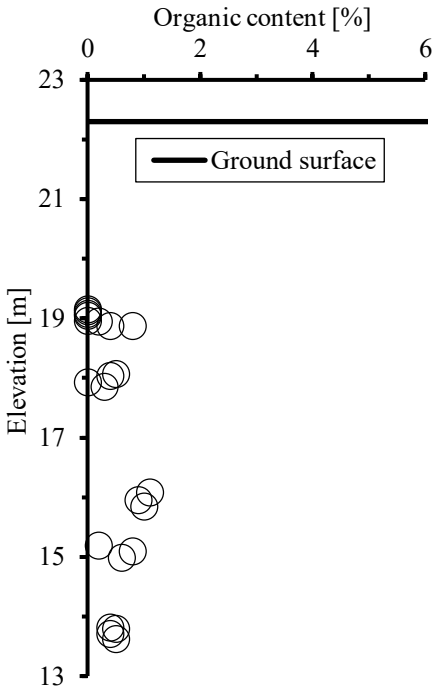

Salinity [g/l]
0
0,5
1
23
21
19
17
15
13
Elevation [m]
Ground surface

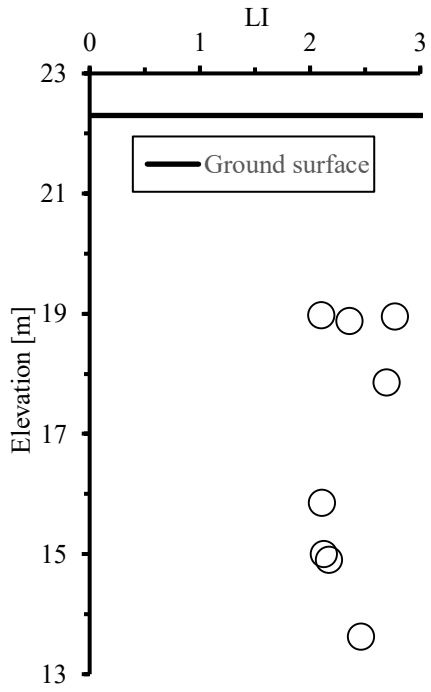
APPENDIX C: PAIMIO SITE INVESTIGATION RESULTS

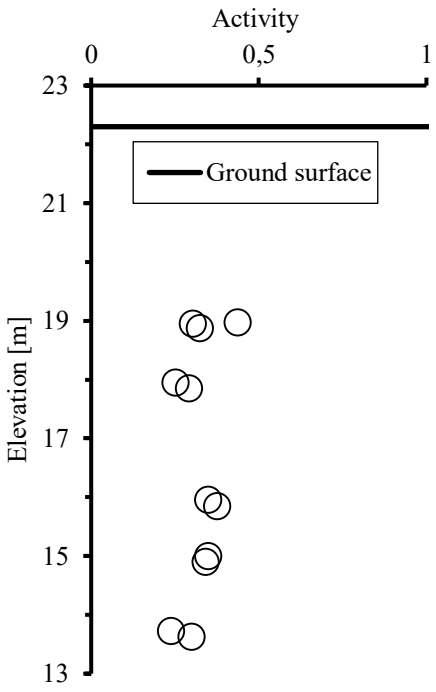


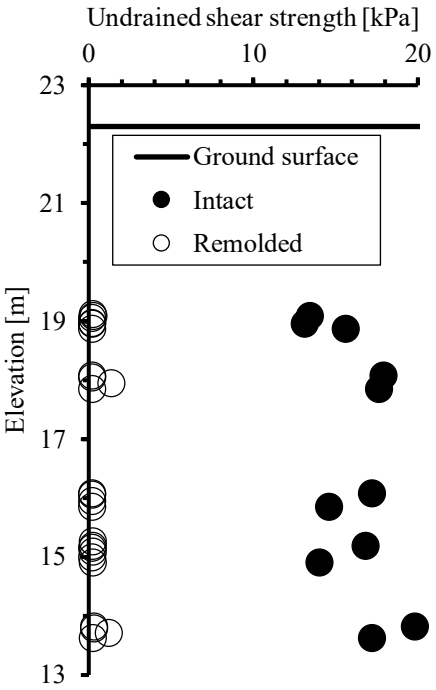


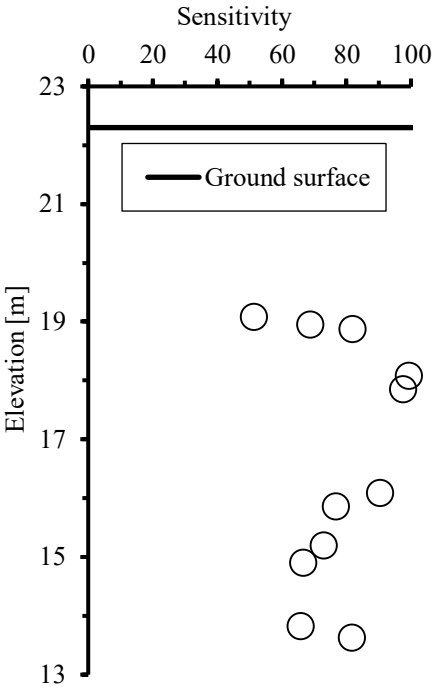

Clay content [%]
0
20
40
60
80
100
23
21
19
17
15
13
Elevation [m]
Ground surface

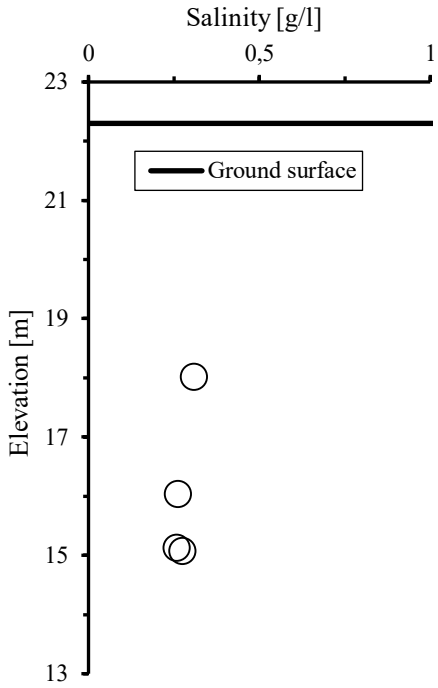

Organic content [%]
0
2
4
6
23
21
19
17
15
13
Elevation [m]
Ground surface


LI
0
1
2
3
23
21
19
17
15
13
Elevation [m]
Ground surface

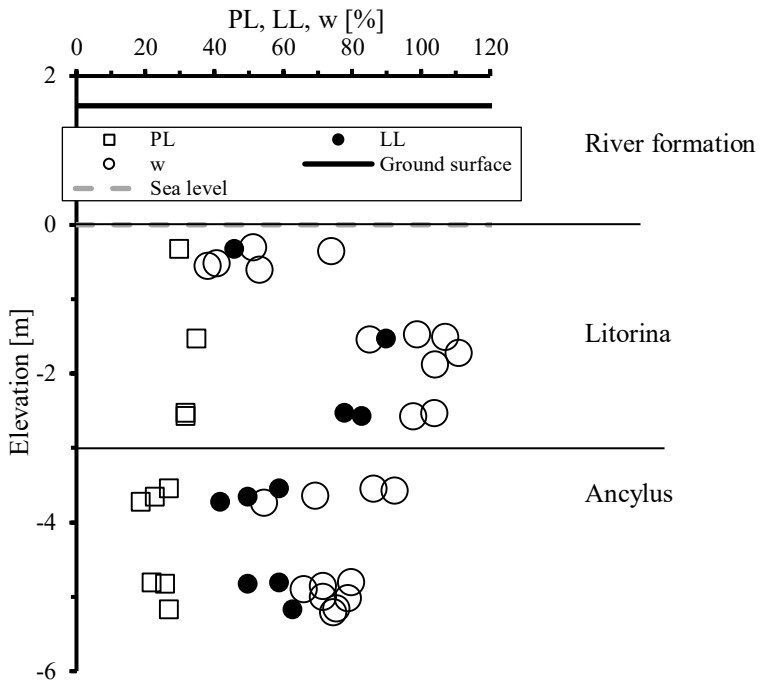

Activity
0
0,5
1
23
21
19
17
15
13
Elevation [m]
Ground surface

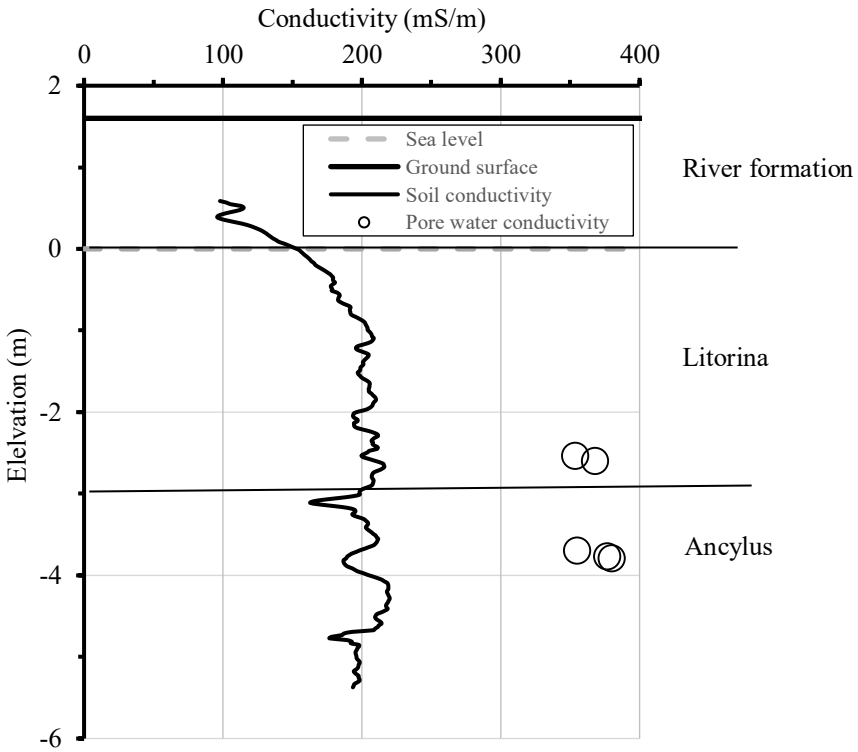

Undrained shear strength [kPa]
0
10
20
23
21
19
17
15
13
Elevation [m]
Ground surface
Intact
Remolded

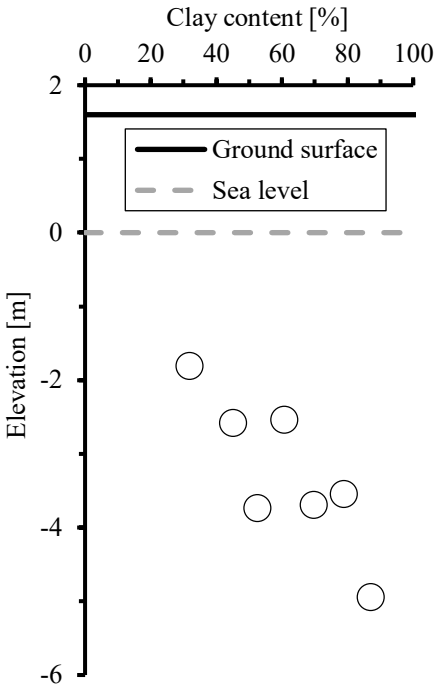

Sensitivity
0
20
40
60
80
100
23
21
19
17
15
13
Elevation [m]
Ground surface

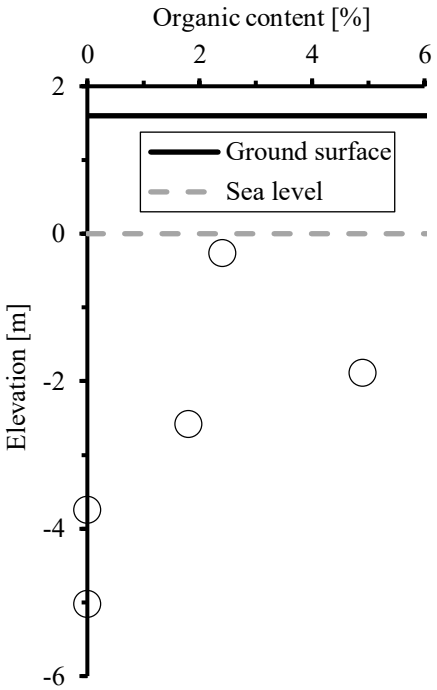

Salinity [g/l]
0
0,5
1
23
21
19
17
15
13
Elevation [m]
Ground surface

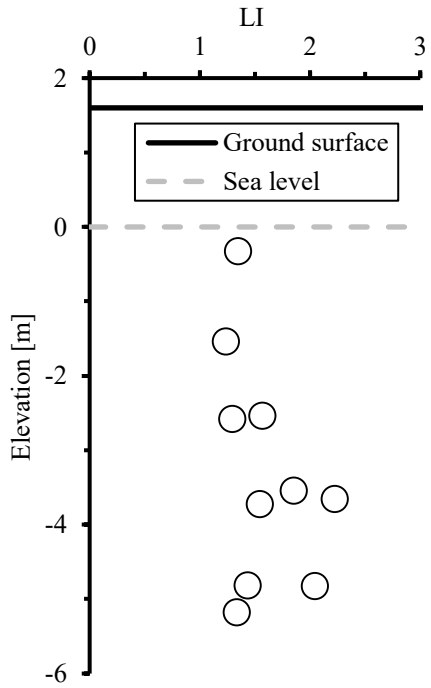
APPENDIX D: KOTKA 238 SITE INVESTIGATION RESULTS

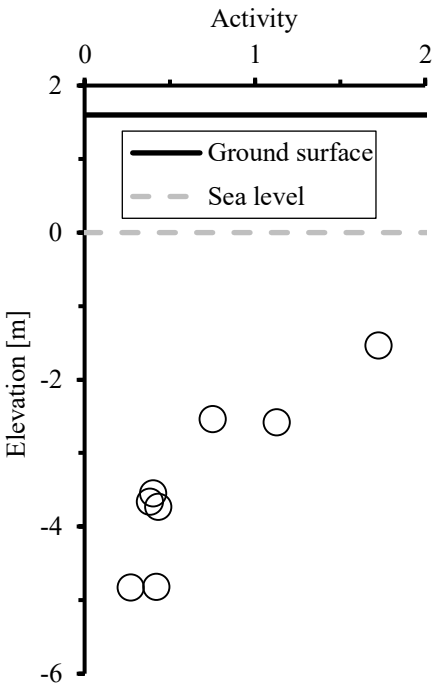


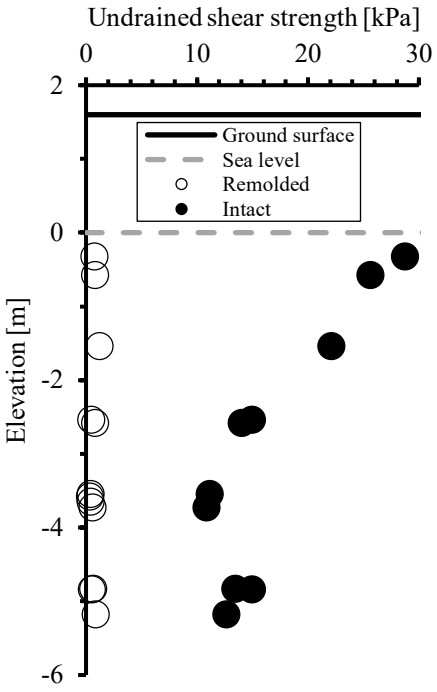


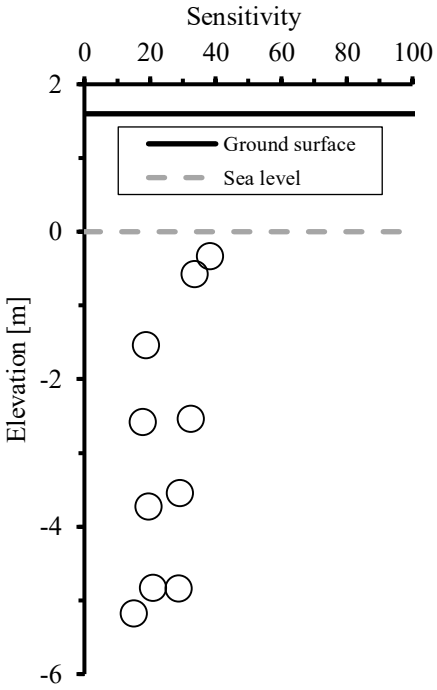

Clay content [%]
0
20
40
60
80
100
2
0
-2
-4
-6
Elevation [m]
Ground surface
Sea level

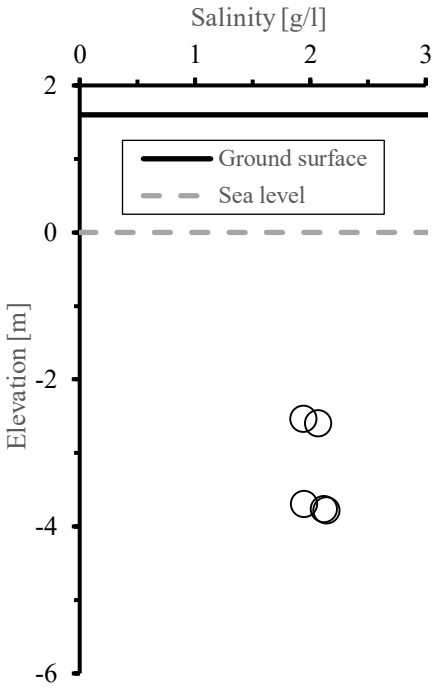

Organic content [%]
0
2
4
6
2
0
-2
-4
-6
Elevation [m]
Ground surface
Sea level


LI
0
1
2
3
2
0
-2
-4
-6
Elevation [m]
Ground surface
Sea level

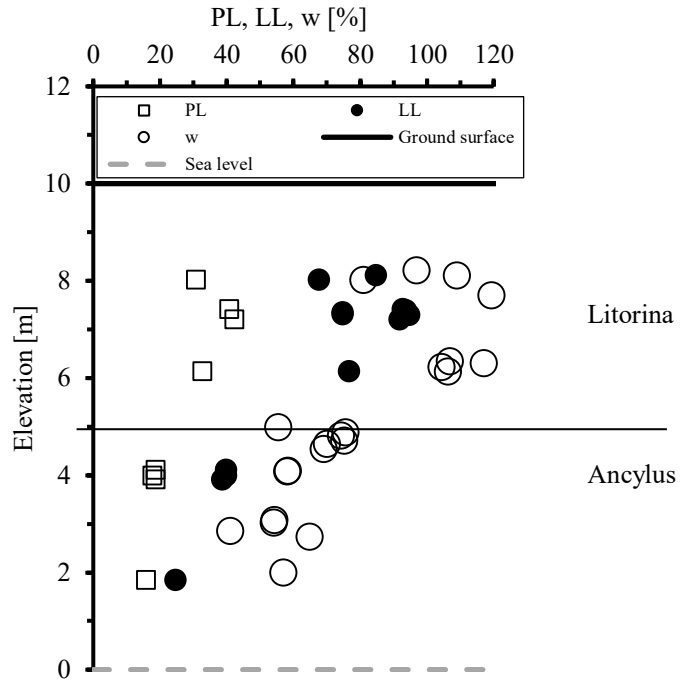

Activity
0
1
2
2
0
-2
-4
-6
Elevation [m]
Ground surface
Sea level

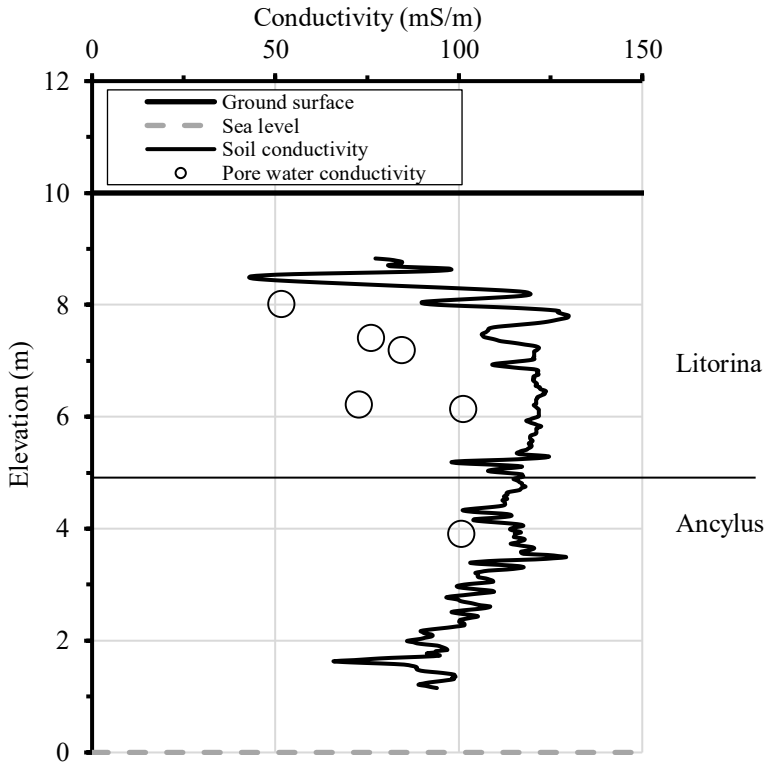

Undrained shear strength [kPa]
0
10
20
30
2
0
-2
-4
-6
Elevation [m]
Ground surface
Sea level
Remolded
Intact

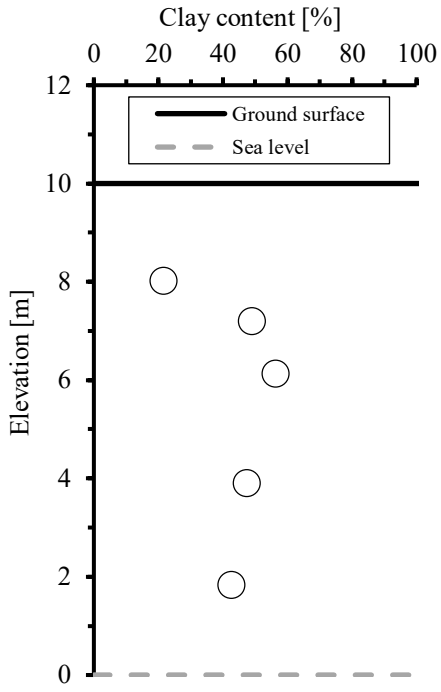

Sensitivity
0
20
40
60
80
100
2
0
-2
-4
-6
Elevation [m]
Ground surface
Sea level

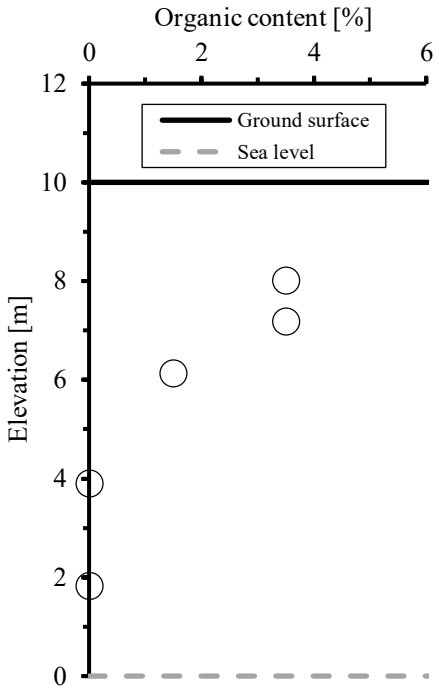

Salinity [g/l]
0
1
2
3
2
0
-2
-4
-6
Elevation [m]
Ground surface
Sea level

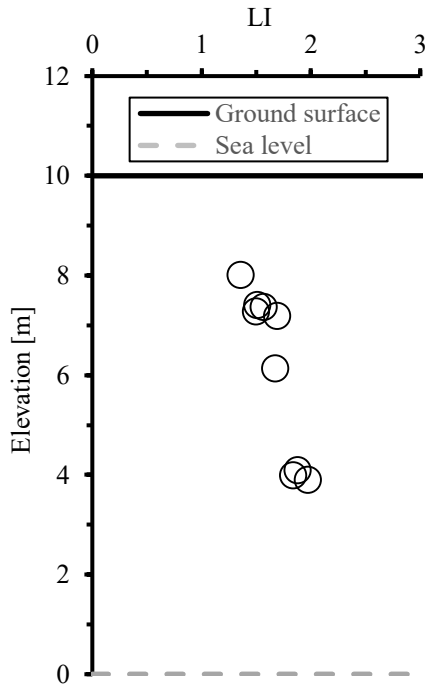
APPENDIX E: KOTKA 233 SITE INVESTIGATION RESULTS

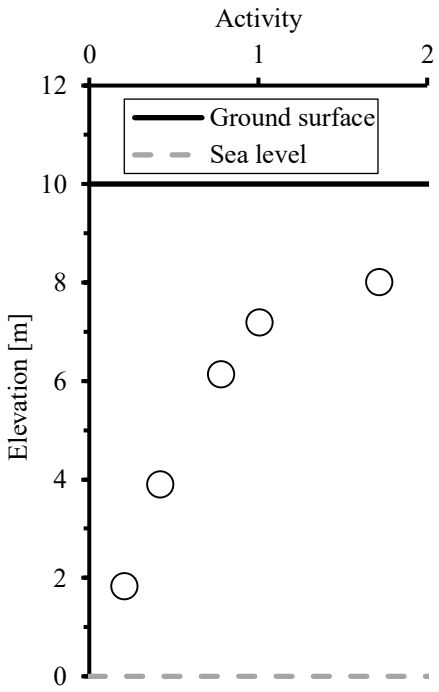


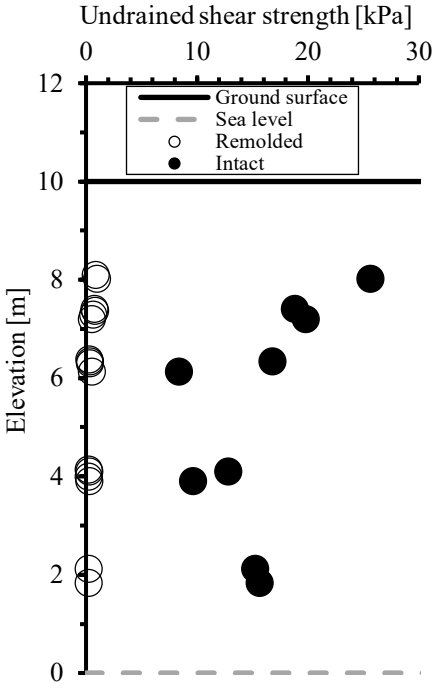


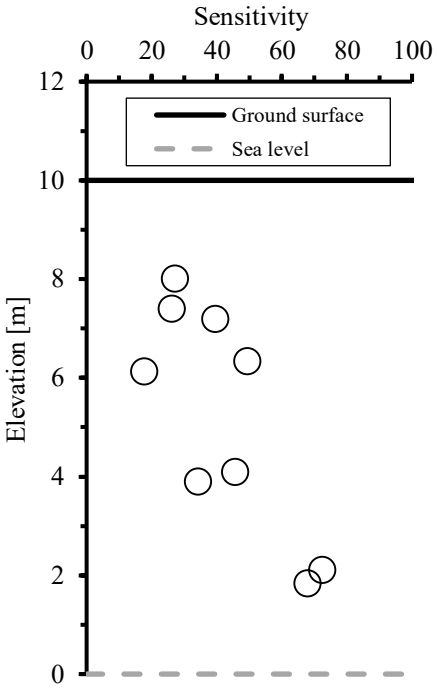

Clay content [%]
0
20
40
60
80
100
12
10
8
6
4
2
0
Elevation [m]
Ground surface
Sea level

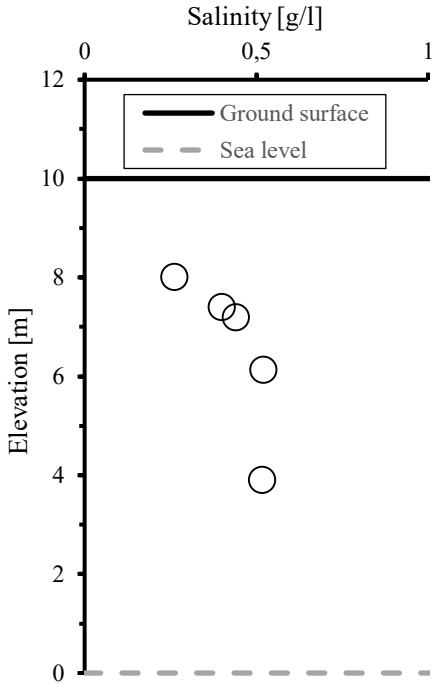

Organic content [%]
0
2
4
6
12
10
8
6
4
2
0
Elevation [m]
Ground surface
Sea level


LI
0
1
2
3
12
10
8
6
4
2
0
Elevation [m]
Ground surface
Sea level

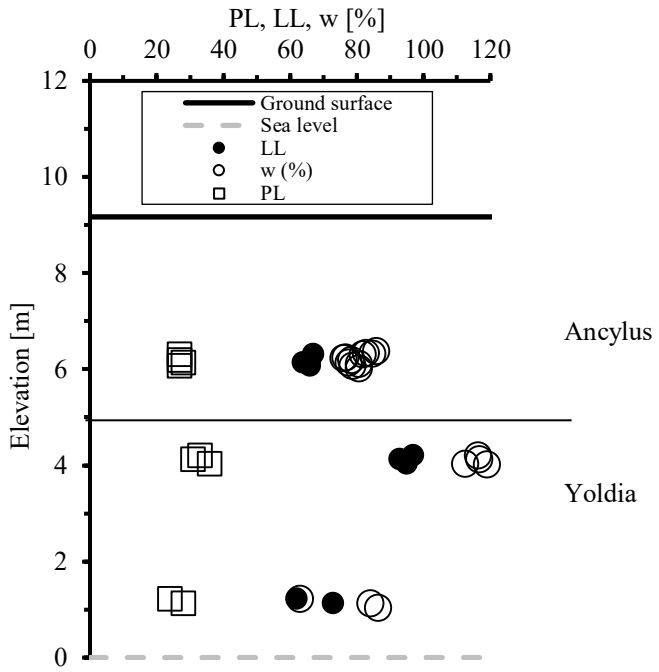

Activity
0
1
2
12
10
8
6
4
2
0
Elevation [m]
Ground surface
Sea level

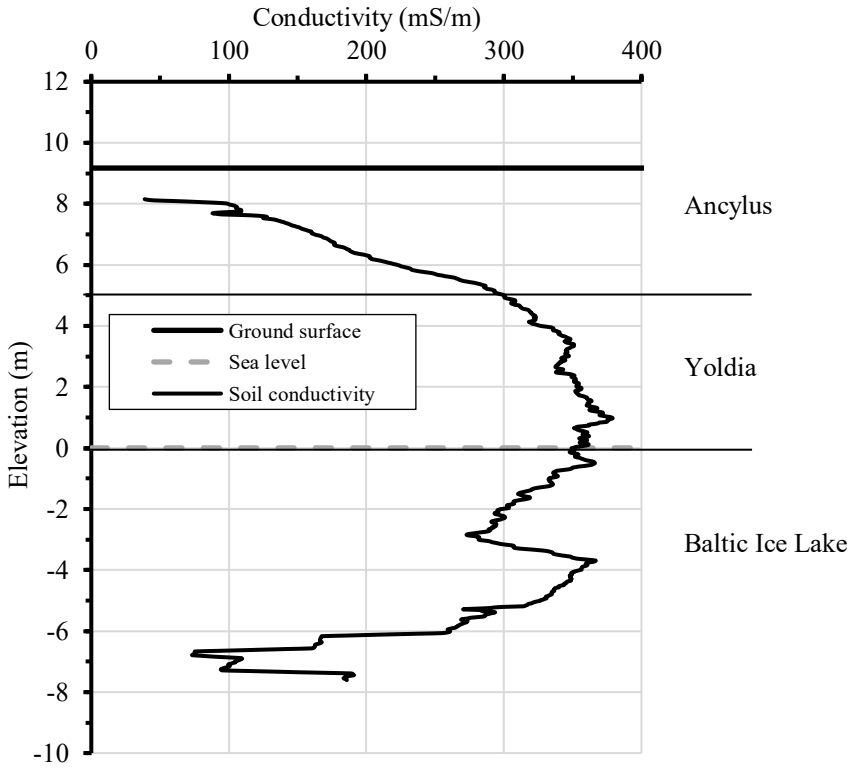

Undrained shear strength [kPa]
0
10
20
30
12
10
8
6
4
2
0
Elevation [m]
Ground surface
Sea level
Remolded
Intact

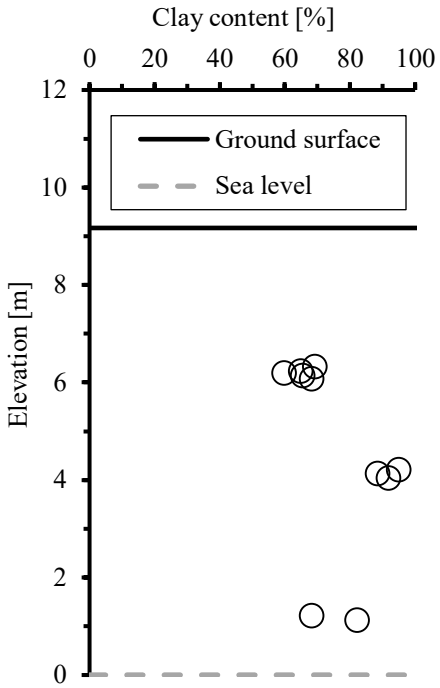

Sensitivity
0
20
40
60
80
100
12
10
8
6
4
2
0
Elevation [m]
Ground surface
Sea level

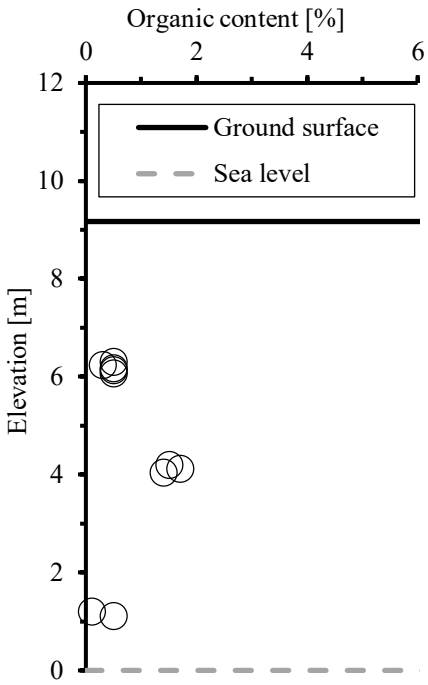

Salinity [g/l]
0
0,5
1
12
10
8
6
4
2
0
Elevation [m]
Ground surface
Sea level

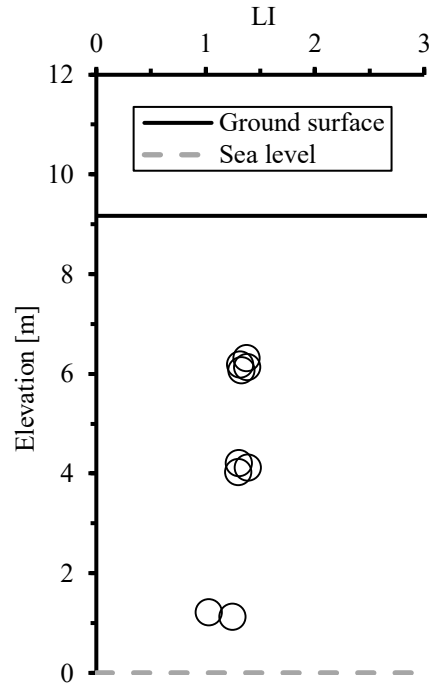
APPENDIX F: MASKU SITE INVESTIGATION RESULTS

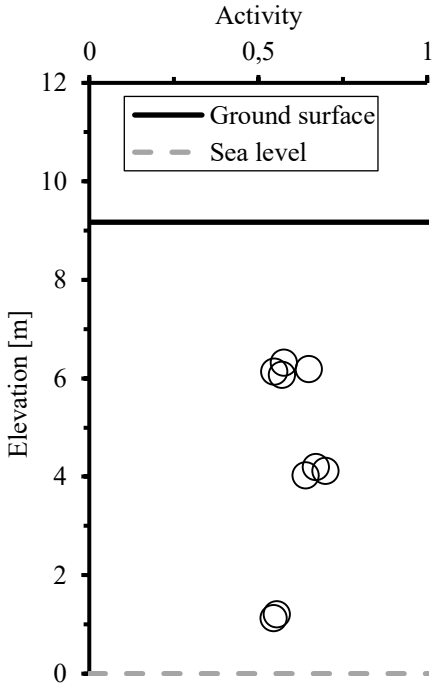


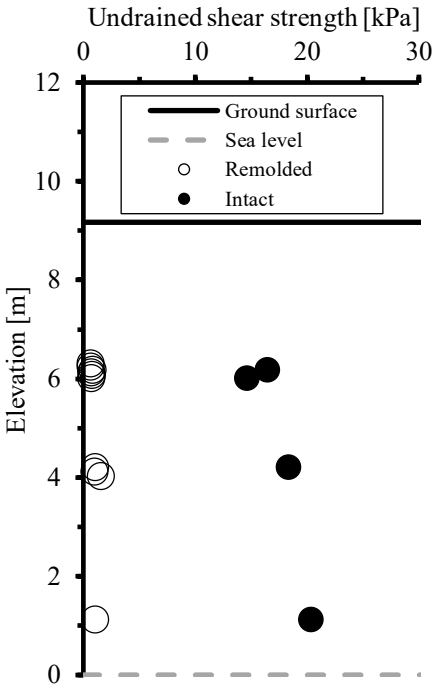


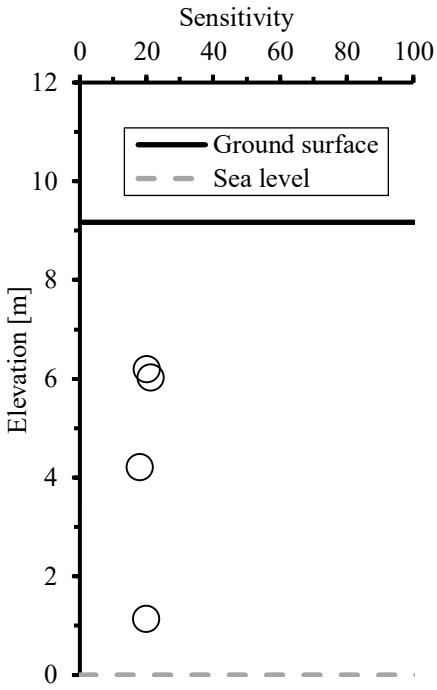

Clay content [%]
0
20
40
60
80
100
12
10
8
6
4
2
0
Elevation [m]
Ground surface
Sea level


Organic content [%]
0
2
4
6
12
10
8
6
4
2
0
Elevation [m]
Ground surface
Sea level

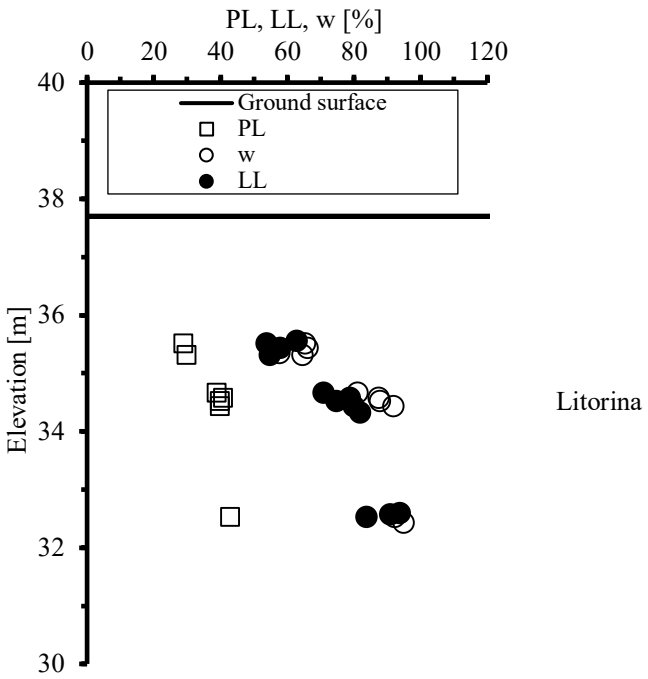

LI
0
1
2
3
12
10
8
6
4
2
0
Elevation [m]
Ground surface
Sea level

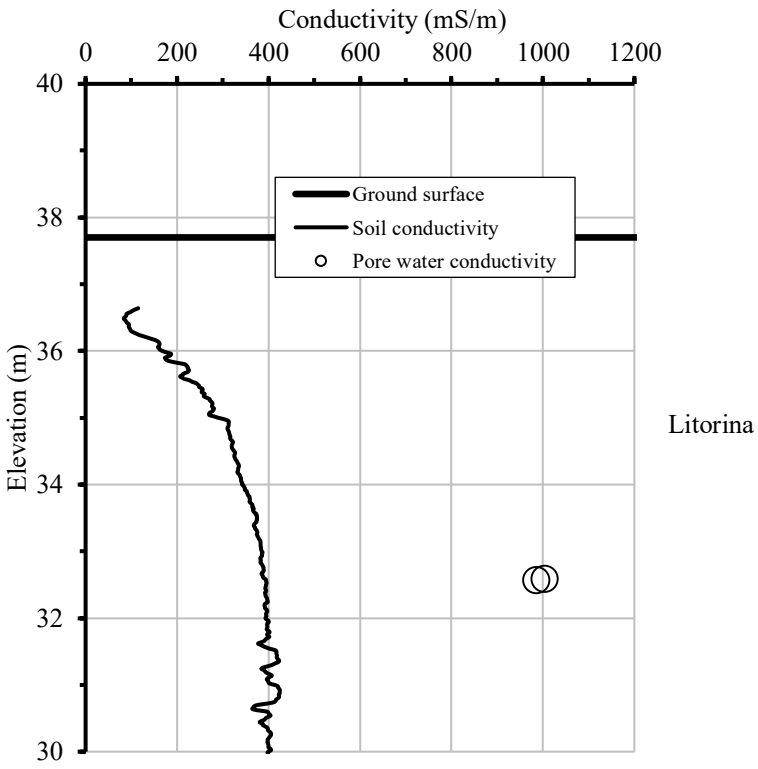

Activity
0
0,5
1
12
10
8
6
4
2
0
Elevation [m]
Ground surface
Sea level

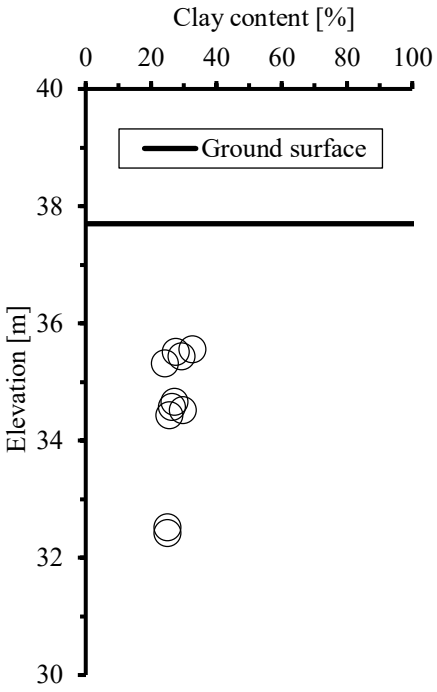

Undrained shear strength [kPa]
0
10
20
30
12
10
8
6
4
2
0
Elevation [m]
Ground surface
Sea level
Remolded
Intact

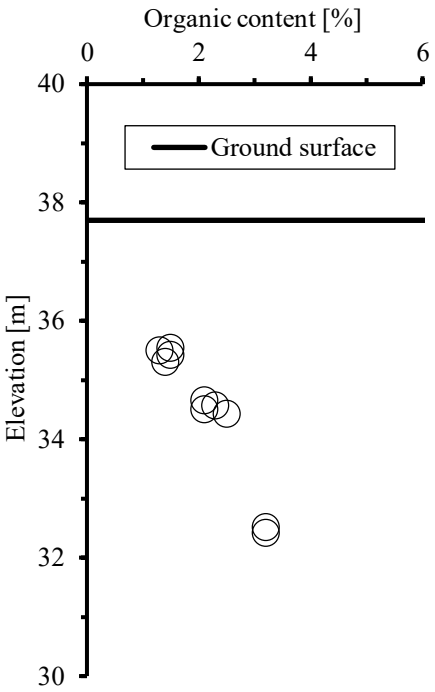

Sensitivity
0
20
40
60
80
100
12
10
8
6
4
2
0
Elevation [m]
Ground surface
Sea level

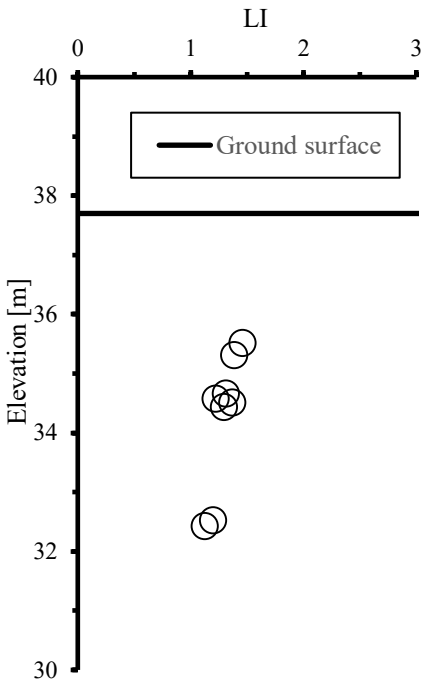
APPENDIX G: MURRO SITE INVESTIGATION RESULTS

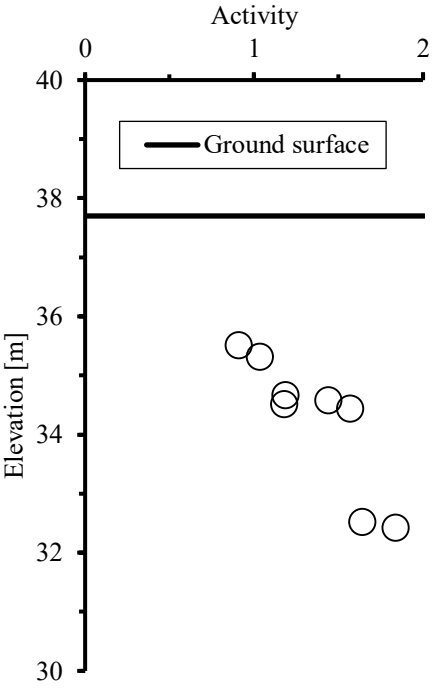


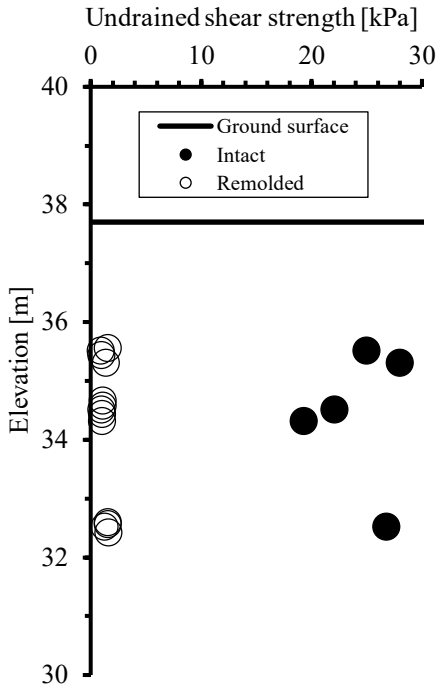


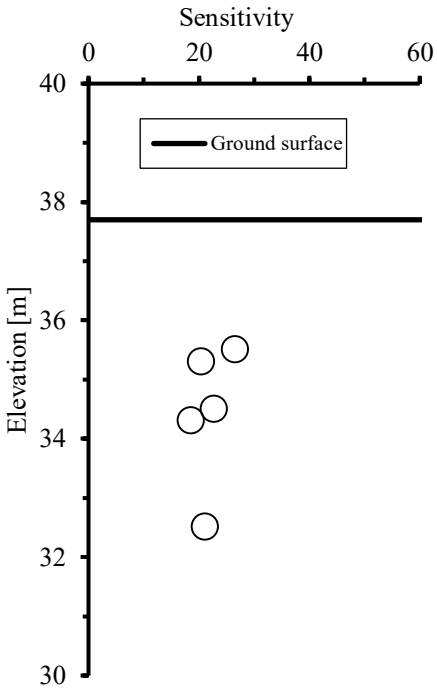

Clay content [%]
0
20
40
60
80
100
40
38
36
34
32
30
Elevation [m]
Ground surface

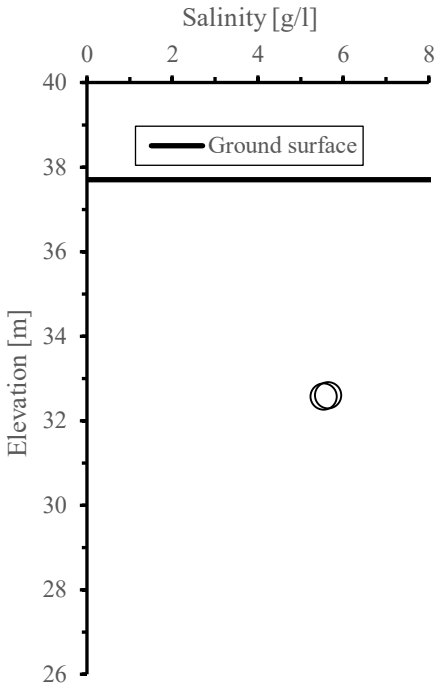

Organic content [%]
0
2
4
6
40
38
36
34
32
30
Elevation [m]
Ground surface


LI
0
1
2
3
40
38
36
34
32
30
Elevation [m]
Ground surface


Activity
0
1
2
40
38
36
34
32
30
Elevation [m]
Ground surface


Undrained shear strength [kPa]
0
10
20
30
40
38
36
34
32
30
Elevation [m]
Ground surface
Intact
Remolded


Sensitivity
0
20
40
60
40
38
36
34
32
30
Elevation [m]
Ground surface


Salinity [g/l]
0
2
4
6
8
40
38
36
34
32
30
28
26
Elevation [m]
Ground surface